ASSESSING THE POTENTIAL OF GEONETCAST EARTH OBSERVATION AND IN-SITU DATA FOR DROUGHT EARLY WARNING AND MONITORING IN TIGRAY, ETHIOPIA

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March, 2012

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Thesis submitted to the Faculty of Geo-Information Science and Earth Observation of the University of Twente in partial fulfilment of the requirements for the degree of Master of Science in Geo-information Science and Earth Observation.
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ABSTRACT

Rainfall is a one of the most dominant factors governing drought occurrences. Its representing at the global, regional as well as local scale is a major issue in drought assessment and early warning. Observing of rainfall in the Tigray region of Ethiopia requires a combination of satellite rainfall and rain gauge data. How ever, Tigray has a sparse weather stations network and lack of skilled manpower to collect the meteorological data and to provide quality reports timely. In this study, the potential of GEONETCast satellite rainfall data was evaluated against other satellite rainfall data, currently used in Ethiopia for drought early warning and also In-situ data.

Drought and food security early warning is currently done in Ethiopia using the LEAP methodology data calculate rainfall-based water requirement satisfaction (WRSI) and crop yield reduction (YR) indices. In this study, an attempt is made to see whether satellite energy balance ET-based WRSI and YR indices, derived from near real time GEONETCast data could be used to perform an independent evaluation of agricultural drought risk and crop failure in Tigray.

Five years (2006 to 2010) meteorological data was collected from Tigray Branch meteorology Office(TBMO) and Ethiopia National Meteorology Agency (NMA). Three years (2008 to 2010) of statistical crop data were obtained from the Tigray Bureau of Agriculture and Rural Development (BoARD). Five month (May to September 2010) of MSGMPE satellite rainfall data were collected, which is produced by EUMETSAT. Daily Evapotranspiration 136 images of (DMET) were obtained from LSA SAF. Decadal RFE2.0 rainfall estimates for the same period, daily FEWS NET (ETo from July 15 to November 30, 2010) and GlobCover 2009 land cover data was used together with field knowledge to classify land cover of the study area.

The results of the rainfall inter-comparison of MSGMPE, RFE2.0, TAMSAT and In-situ station data showed that MSGMPE 3-km data permitted a good assessment of areal rainfall in Tigray (for 2010). Further use of MSGMPE can be recommended to generate daily or decadal district rainfall amounts with good accuracy.

The comparison of the satellite ET-based WRSI and YR from GEONETCast data with LEAP standard output (WRSI and YR) and crop yield statistics from Tigray BoARD, showed that there is potential to use satellite ET from GEONETCast to evaluate crop drought stress and yield reduction in the Tigray region.

The GlobCover (2009) dataset did not permit reliable assessment of seasonal rain-fed land cover in the Tigray region, and own field knowledge and other sources were needed to generate rain-fed land cover information. More ground validation for land cover is needed to use these satellite land cover data for operational purposes.

It can be conclude that MSG-based satellite rainfall estimation and ET-based drought indices (WRSI and YR) derived from GEONETCast, can help us for decision making in agricultural drought early warning and monitoring in Ethiopia. In this study application is tested especially in areas like Tigray where weather and other monitoring stations are sparsely available, and drought prone areas are very present who require close monitoring for drought and agricultural production and livelihood protection.

Key words: satellite rainfall, satellite evapotranspiration, drought, water requirement satisfaction index, crop yield reduction, GEONETCast, LEAP.

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Acronyms and Abbreviations

Term	Description
AMSU	Advance Microwave Sound Unit
BoARD	Bureau of Agriculture and Rural Development
CPC	Climate Precipitation Centre
DMET	Daily Mean Evapotranspiration
ETa	Actual crop evapotranspiration
ETo	Reference crop evapotranspiration
FEWS NET	Famine Early Warning System Network
GNC	GEONETCast
GPI	GOES Precipitation Index
GTS	Global Telecommunication Station
IDW	Inverse distance weight
ILWIS	Integrated Land and Water Information System
kc	Crop coefficient
ky	Crop yield response
LEAP	Livelihood Early Assessment and Protection
LSA-SAF	Land Surface Analysis-Satellite Application Facility
MERIS	Medium Resolution Imaging Spectrometer
MET	Meteosat Evapotranspiration
MOA	Ministry of Agriculture
MPE	Multi-Sensor Precipitation Estimation
MSG	METEOSAT Second Generation
NMA	National Meteorological Agency
NOAA	National Oceanic and Atmospheric Administration
PDMET	Pixel based daily mean evapotranspiration
R^2	Coefficient of determination
RFDMET	Rain-fed land cover daily mean evapotranspiration
RFE2.0	Satellite rainfall estimation version2.0
RMSE	Root Mean Square Error
SAF	Satellite Application Facility
SSM/I	Special Sensor microwave Imager
TAMSAT	Tropical Application of Meteorology using SATellite data and ground based observation
TMBO	Tigray Meteorology Branch Office
USGS	Urinated State Geological Survey
WDMET	Aggregated wereda daily mean evapotranspiration
WR	Water Requirement or
WRSI	Water Requirement Satisfactory Index
YR	Yield Reduction

1. INTRODUCTION

1.1. Background

Rainfall is a one of the most dominant factors governing drought occurrences. Its variability at the global, regional as well as local scale is a major element in drought assessment and early warning. The variability of rainfall in Tigray region of Ethiopia requires a combination of satellite rainfall observations and rain gauge data in order to improve the spatial rainfall monitoring and assessment resolutions, which can help for drought early warning and monitoring. The combination of sparse, unevenly distributed network of gauges and lack of skill manpower for data collection and timely reporting in most of the weather network stations would benefit from additional satellite rainfall estimation. Remote sensing data can help to solve the problem of unreliable and poor spatial coverage of ground observation networks and can help to minimize the delay of reporting and uneven quality control (Senay and Verdin, 2003). The accuracy and amount of point rainfall estimation and assessing both the spatial and temporal variability of rainfall is not easy., (Thomas, 2003).

There is no universally accepted and precise definition of drought. But, most drought types originate from insufficient amount of precipitation (Wilhite and Glantz, 1987). The definition a drought varies based on its functional description like hydro meteorological drought. Socioeconomic factors, and the supply and demand of water are the major characteristics that create an obstacle for the lack of a precise and universal definition of drought, (Mishra and Singh, 2010b). A generally accepted definition of drought by UNCCD,(2007) is " A naturally occurring phenomenon that exists when low precipitation is prevailing for an extended period of time, which causes serious hydrological effect that adversely affects land resource production systems". Meteorological, hydrological, agricultural and socio-economic droughts are the main category classes of drought (Mishra and Singh, 2010b).

According to Kirill et al. , (2002) and Mishra and Singh, (2010b) a drought is one of the most threatening phenomenon and environmental disaster which may occur even in low and high rainfall areas. Hydrological effects on land resource production systems mostly lead to failure of agricultural production (UNCCD, 2007). Therefore, precipitation has a direct effect on population and environment that aggravates famine, disease and death (Kirill et al., 2002).

Drought is regularly observed in various parts of Ethiopia. The effective and timely prediction of droughts and the use of early warning and monitoring systems is advocated by national, regional and local authorities in Ethiopia but relatively little has been done on drought prediction and early warning so far. Drought risk management, preparedness and mitigation are important elements of drought forecasting (Mishra and Singh, 2011).

Geographic Information System (GIS) and remote sensing can provide timely drought early warning and monitoring (Chopra, 2006). The Ethiopian organizations uses the Livelihood Early Assessment and Protection (LEAP) software program which mainly depends on weather data for drought early warning and monitoring on 10-day and 0.1°(~10 km) temporal and spatial resolutions respectively (Hoefsloot, 2010). Nowadays rainfall in Ethiopia is dominated by erratic, late onset and early cessation during the main rainy season (kiremet) (Beyene and Meissner, 2010).

Representing the variability of rainfall in the country requires near real-time datasets in order to improve the reliability of early warning and drought monitoring. The Faculty of Geo-Information Science and Earth Observation Institute (ITC) of the University of Twente (UT) is conducting a pilot project for UN-WFP, the Disaster Risk Management and Food Security Sector (DRMFSS) and National Meteorological Agency (NMA) in Ethiopia. The aim of this pilot project is to use near real-time GEONETCast (GNC) data streams for improving the spatial and temporal resolutions for early warning and risk assessments in Ethiopia for later use in LEAP and other assessment and mitigation protocols. The GEONETCast toolbox http://www.itc.nl/pub/WRS/WRS-GEONETCast is developed to acquire and manage real-time satellite imagery. It is built using the ILWIS software http://52North.org and freely available for use with a high degree of data analysis and transfer capability.

This study aims to improve spatial resolution of LEAP standard output for early warning and drought monitoring using GNC data stream. To the knowledge of the author, there are few attempts to predict and understand droughts in the Tigray region. However, there is no study carried out to improve drought early warning and monitoring using GNC stream datasets and to compare LEAP standard outputs with In-situ food production measurements through timely forecasting and monitoring of drought.

1.2. Problem statment

Drought is a natural hazard and a threat to people's livelihood, which is directly related to lack of moisture for the crop production. The sub-Saharan part of Africa is more drought prone area (Asheber, 2010). Ethiopia is part of the sub-Sahara African countries that has been affected by recurrent droughts for the last century that caused extreme human suffering, and had a disastrous effect on agriculture and livestock production with consequences that are apparent even today. Since 1970s and 1980s drought was occurred every 10 years but recently mostly it occurs every two to three years at a regional scale (Margaret, 2003).

Consequently, the need for effective, timely and reliable drought monitoring is relevant in order to reduce, to manage the impacts of drought and to prevent it from turning into famine. This requires developing a holistic approach to drought early warning and monitoring that is capable of characterizing and timely assessing droughts at different in time-space dimensions. The possible prediction and monitoring of drought disasters requires relevant information regarding the disaster in real time, which requires extensive scientific and technological inputs for data collection, analysis and drought forecasting.

The Ethiopian organizations are currently using LEAP software which is developed by World Food Program (WFP) and World Bank to quantify and to index agricultural drought and rainfall estimations which depends on ground and satellite rainfall data and agro-meteorological data which convert data into crop production or rangeland estimates and possible yield reductions (Hoefsloot, 2010). Subsequently, it creates livelihood stress indicators for vulnerable populations who rely on rain-fed agriculture. The main drawback of LEAP standard output indices is the rather coarse 0.1°(~10 km) spatial resolution and it is depending on data collected at weather stations. Thus improving spatial resolution is pertinent and would be an asset. For this study this assured that GNC can ensure a more timely and effective response to provide spatially continuous information in near real-time.

This research attempts to compare and to evaluate the spatial resolution of LEAP standard output of weather-based drought indices and GNC derived output based on satellite estimates. Both estimates are ground verified for the Tigray region using agricultural statistics and field data. This could ultimately play a role to improve the timely prediction and to assess more reliable drought early warning and monitoring at a higher spatial resolution.

1.3. Objectives

The main objective of this research is to assess the potential of GEONETCast satellite data and In-situ data to improve drought early warning and monitoring, with focus in the Tigray region.

The purpose of GNC is to supply data streams with spatial resolution of 1-3 km as compared to the standard LEAP output spatial at ~10 km * ~10 km resolution. Currently GNC data permits to increase the resolution from 10 km to 3 km, pending the dataset standard output using GNC data stream. Few efforts had been done to predict and understand droughts in Tigray region but GNC stream datasets approaches has not been carried out to improve drought early warning and monitoring and to compare those to LEAP standard outputs and In-situ agricultural production measurements.

The specific objectives of the study are:

- To compare MSGMPE rainfall estimates with RFE2.0 estimates that are currently used in LEAP and TAMSAT rainfall estimates and In-situ NMA rainfall data using the year 2010 as sample. It estimates are at decadal and 10 km temporal and spatial resolution respectively.
- To compare and evaluate LEAP's standard outputs water requirement satisfaction index (WRSI) and yield reduction (YR) to GNC datasets derived outputs, based on satellite estimates of evapotranspiration (LandSaf-MET). A comparison is also to ground observations from the BoARD (Bureau of Agriculture and Rural Development –Tigray region).
- To improve spatial accuracy and early warning lead time of LEAP outputs (food early warning).

1.4. Research questions

- Does MSGMPE data provide a better spatial accuracy for rainfall estimation over RFE2.0 and TAMSAT data?
- Can the use of GNC near real-time satellite estimates of evapotranspiration (ET) give reliable output for drought indices – WRSI and YR estimates - as compared to LEAP standard output?
- How can the spatial accuracy of LEAP standard output be improved for drought early warning and food security by using GNC data?

1.5. Hypothesis

METEOSAT Second Generation (MSG-MPE) and other GNC datasets are reliable data for drought early warning and monitoring. The RFE2.0 dataset is a rainfall input data for LEAP used by DRMFSS in Ethiopia for drought monitoring and early warning, but has low spatial(~10 km) and temporal (10 day) resolution. The application of GNC rainfall data MSG-MPE and evapotranspiration data Landsaf-MET that have relatively high spatial resolution may improve a significant effect in improving spatial accuracy for drought prediction, monitoring and early warning.

1.6. Organization of the thesis

This thesis document is organized in six chapters: chapter one contains an introduction followed by problem statement, research objectives, research questions and hypothesis. Chapter two includes the basic thesis concepts literature review will presented. Chapter three describes the study area and data collection. Chapter four contains Methodology of the research. Chapter five present the result and discussions. Chapter six include conclusion and recommendations of the thesis and limitations of the study.

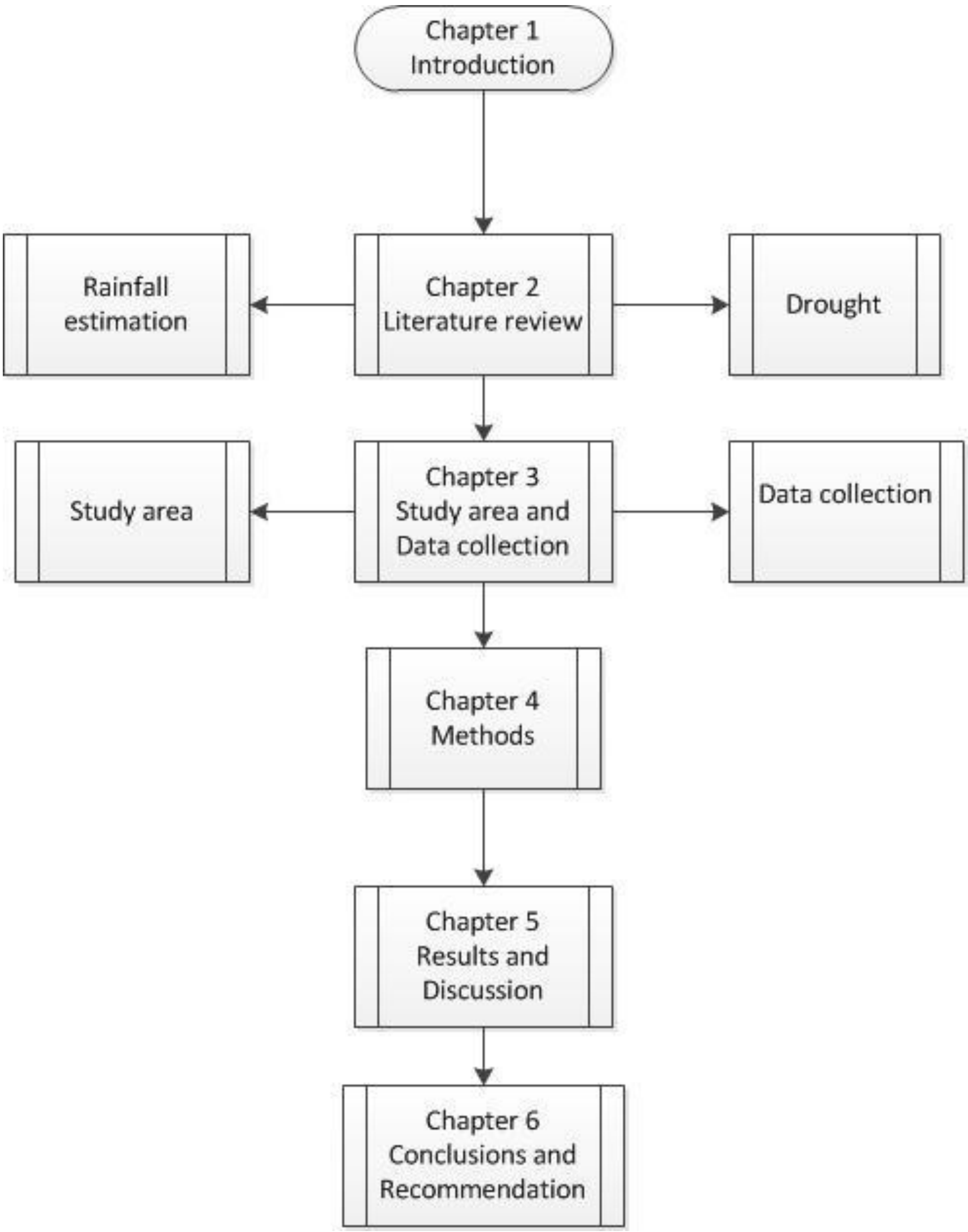

Figure 1-1: Thesis organization

2. LITERATURE REVIEW

2.1. Drought

2.1.1. Issue of drought in Ethiopia

Rain-fed agriculture is the main economic source in most sub-Saharan Africa which is characterized by low and erratic nature of rainfall and often leads to water shortage and droughts (The World Bank et al., 2010), (Tao et al., 2003) and (Asheber, 2010). Gebrehiwot et al., (2011) note that water shortages, economic losses and adverse social consequences are significantly increased frequently both spatial and temporal. Around 30 major droughts occurrences were registered in the country of which 13 of them are covered at national level and reported as severe drought in the past nine centuries (Gebrehiwot et al., 2011).

Ethiopia has affected by recurrent droughts, from 1970 to 1998 some 56 large-scale disasters are reported with an estimated 66 million people affected (Margaret, 2003). Since 1985, the frequency of droughty has increased. In 2002 severe conditions of drought in some part of the country are reported, with an estimated 10 to 14 million exposed for food aid (Margaret, 2003).

2.1.2. Drought mechanism

Many definitions of drought occur because the characteristics of drought differ from region to regions and this leads to some confusion to define a drought. However, Wilhite and Glantz, (1987) note that a drought can be defined as in two categories, following conceptual and operational definitions. Conceptual definition of droughts focuses on the prolonged insufficient precipitation while operational definitions help to identify the beginning, termination, and degree of severity of the drought. Also droughts can have specific characteristics that are described by its magnitude, duration, location and timing (Below et al., 2007). This may demands a multi-disciplinary approach of all the scientists like environmentalists, ecologists, hydrologists, meteorologists, geologists and agricultural (Mishra and Singh, 2010b).

Drought can be categorized in to four major groups

1. Meteorological drought is related to duration of dry period with insufficient amount of precipitation, that contains 70% below normal which causes soil moisture depletion that aggravate agricultural droughts (Wilhite and Glantz, 1987), therefore, it occurs more frequently than the other drought (Jonathan and Angela, 2006) .

2. Hydrological drought occurs after long period of insufficient precipitation leads to low surface and sub-surface water level and there is no direct relationship between the amount of precipitation and availability of surface and subsurface water supply (Jonathan and Angela, 2006).

3. Agricultural drought is commonly related to soil moisture deficits during the growth stages that cause crop failure. Soil moisture availability can not only affect by precipitation but availability also depends on

water holding capacity of the soil that affects the amount of soil moisture content of the area(Wilhite and Glantz, 1987).

4. Socio-economical droughts are related to when the shortage of water is affecting the people with low incomes and is refers to the supply and demand of economic goods like electric power (Mishra and Singh, 2010a). There is no a direct relation between the low precipitation and socio-economic droughts since changes in management may reduce or aggravate this type of drought (Jonathan and Angela, 2006). For instance appropriate farming practice together with soil water conservation activities reduce the impact of drought even during insufficient amount of rainfall (Jonathan and Angela, 2006).

2.1.3. Drought indices

There are a number of climate based drought indices and vegetation indices used to forecast and to monitor drought early warning. Some of them are; Percent of Normal, standard precipitation index (SPI), Normalization Differences Vegetation index (NDVI) Vegetation Condition index (VCI), Palmer drought severity index (PDSI), Crop Moisture Index (CMI), surface water Supply Index(SWSI), reclamation drought Index(RDI) and Temperature condition index (TCI) (Gebrehiwot et al., 2011) and (Gadisso, 2007).

Nowadays the remote sensing based drought index uses a combination of the Land Surface Temperature (LST), NDVI and precipitation data from MODIS and TRMM satellite and provides accurate drought prediction (Rhee et al., 2010). Drought forecasting, dissemination of warnings, preparedness measures and reaction capacities are the main elements of early warning system (Mishra and Singh, 2011). Famine Early Warning System Network (FEWS NET) provide satellite image products that can be used for early warning and drought monitoring (Hutchinson, 1991). ISDR., (2003) points out that remote sensing data helps to minimize the effect of drought and to provide timely response.

The relationship between annual rainfall and NDVI is a quick strong although NDVI measures the greenness of the vegetation and does not measure crop yield and this is one of the drawback satellite derived NDVI for drought monitoring (Gadisso, 2007). Since the mid-1980s satellite vegetation index imagery has been used to identify seasonal landscape anomalies which are indicators of drought (Hutchinson, 1991), and in semi-arid sub-Saharan Africa both precipitation, temperature humidity of the earth's surfaces and vegetation cover can be obtained from space observations of different expressions of drought phenomena (Kirill et al., 2002). To adapt the traditional methods of climate monitoring for famine early warning encourages the use of remote sensing data and Geographic Information System (GIS) to improve the link between climate change and rainfall dynamics (Verdin et al., 2005).

2.1.4. Water Requirement Satisfaction Index and Yield Reduction

Victor.,(1988) pointed out that rain-fed based crop performance can be assessed using water requirement satisfaction index (WRSI). WRSI has an indicator of the crop performance based on the amount of water during the growing period of the crop to satisfy its demand (Richard., 1998). Crop water balance can be estimated based on the onset and termination of the rain season ,where the onset of rain is recognized at least 25 mm of rainfall in first decade followed by a minimum of 20 mm rainfall for two consecutive decades (Senay and Verdin, 2003).

WRSI is a geospatial model developed by the Food and Agriculture Organization (FAO) for use with satellite data to monitor water balance for rain-fed crop throughout the growing period (Frere and Popov,

1986) and this is extended by USGS to support FEWS NET monitoring (Senay., 2009). WRSI is the ratio of the total amount of rainfall supply (ETa) to the total water demand of the crop during the growing season (WR) (Senay and Verdin, 2003).

According to Senay and Verdin (2003) WRSI-based yield estimates using long-term average climate data provide information one month earlier to the seasonal crop assessment. Nowadays in Ethiopia crop yields are predicted by the amount of available water as compared to the crop water requirement for the growing season using a LEAP software that was developed by world Food programme (WFP) (Hoefsloot, 2010).

The yield reduction (YR) can be estimated from the water balance output (Hoefsloot, 2010) (see equation 4-11). Yield reduction can also directly estimated from MET but meteorological satellite cannot estimate for individual crops rather it gives the availability of water for crop production in the area (Oroda, 2002).

2.1.5. Satellite-based drought early warning

2.1.5.1. Famine Early Warning System NETWORK

Famine Early Warning System NETWORK (FEWS NET) is established jointly by U.S. Agency for International Development (USAID) partners with NASA, National Oceanic and Atmospheric Administration (NOAA), U.S .Geological Survey (USGS) and U.S. department of Agriculture in the united states it serves by providing timely drought conditions based on satellite remote sensing data (Pellerin, 2008). FEWS NET provides information earlier one to two months period during food problem (Pellerin, 2008).

2.1.5.2. Global Monitoring Food Security

Global monitoring food security (GMFS) is developed by the European Space Agency (ESA) to improve satellite based and ground truth data to support food aid from local to global level for food security decision-makers (GEOSS, 2012). It also serves as an operational system for food security at local , national and global level that provides early warning and agricultural monitoring activities in Africa (Gilliams, 2011). Ethiopia MOA is one of the receives crop yield and vegetation monitoring (CYVM) 2-3 days after every 10 days from MERIS RR fAPAR products which is delivered from ESA on daily basis (Gilliams, 2011).

2.2. Rainfall estimation

Rainfall is one of the key components of hydrological cycle (Brutsaert, 2005). The accuracy and amount of point rainfall is not easy to estimate by issues of spatial and temporal variability (Thomas, 2003). Satellite rainfall estimations are affected by season, region and elevations of the area, however they provide an alternative source of rainfall data for hydrological applications especially in areas where rain gauges stations are sparsely available (Romilly and Gebremichael, 2011). Gebrehiwot, et al (2011) point out inverse-distance moving average interpolation technique in the ILWIS software is a good methods to spatially interpolate rainfall that creates drought severity maps which is suitable in areas having highly varying of topography like Tigray.

According to Thomas.,(2003) the EUMETSAT Multi-Sensor Precipitation Estimate (MPE) uses the combination of a direct (SSM/I) and indirect rain rate retrieval (MSG IR brightness channel) that have a higher accuracy and higher spatial and temporal resolutions. Rainfall estimation from satellite developed in

MPE gives continuous and accurate rainfall data and this is related to IR brightness temperature for the rain rate retrieval which is suitable for both tropical and subtropical convective precipitation areas and thus the quality of meteorological products are improving using MSG data (Thomas, 2003). Nowadays satellites can provide reliable information rainfall according to Jenifer et al.(2010) 80% correlation was reported between blended TRMM_MSG and ground truth rainfall data in 3 km and 15 minute spatial and temporal resolution respectively. MSG satellite are suitable for drought early warning in Africa due to high temporal resolution (Fensholt et al., 2006).

2.3. Estimation of evapotranspiration

Evapotranspiration is a combination of water lost from both vegetation and bare land through transpiration and evaporation respectively. It is mostly affected by climatic data which can be estimated from reference evapotranspiration from Penman-Monteith (Richard., 1998). Daily evapotranspiration is an important element for crop water requirement that can be estimated from remote sensing (Wassenaar et al., 2003).

2.4. GEONETCast stream datasets

GEONETCast toolbox http://www.itc.nl is built in ILWIS software developed at ITC. GNC provides local., regional and global environmental datasets via satellite communication system and has near real-time data processing (Maathuis and Mannaerts, 2011). It is freely available and it has high degree of data transfer which acquires and manages real-time satellite imageries, used to determine flood, drought and agricultural conditions that uses for environmental monitoring (Maathuis et al., 2008).

Meteosat Second Generation (MSG) geostationary satellite developed by European Space Agency (ESA) and European Organization for the Exploitation of Meteorological Satellites (EUMETSAT). It is one of the geostationary satellites located in the equatorial plane at altitude of about 36,000 km above the earth and provide information with 15-minute temporal resolution and 3km spatial resolution for full- disk imaging and the High Resolution Visible (HRV) contains 1 km spatial resolution and has always viewing the same area (Jeniffer et al., 2010; Johannes et al., 2004). GEONETCast provides near real-time stream datasets such as MSG-MPE, LSA-SAF and FEWS NET product etc that acquires data for early warning and drought monitoring (Maathuis and Mannaerts, 2011).

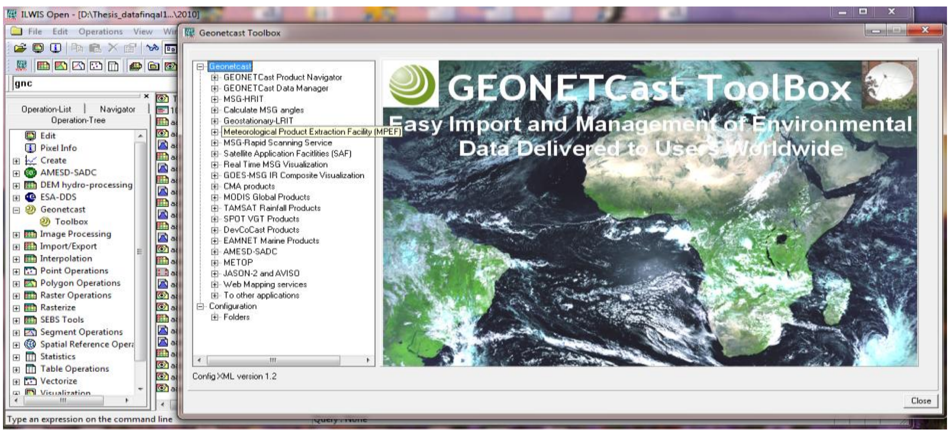

Figure 2-1: GEONETCast toolbox

The Multi-Sensor Precipitation Estimation (MPE) product consists of the near-real time rain rate in mm/hr for each Meteosat image in original pixel resolution 3 km and is most suitable for convective precipitation in areas with poor or no radar coverage like Africa and Asia (Thomas et al., 2002).

2.5. Livelihood Early Assessment and Protection

Livelihood Early Assessment and Protection (LEAP) is GIS software made for Ethiopian government. It uses fixed built-in background images and automatically connects to the internet to download images (Hoefsloot, 2010). It provides weather based indices that interpret early warning information into early response via an established social protection framework like the multiple donor-sponsored (The World Bank et al., 2010). Rainfall, evapotranspiration, water balance ,soil moisture and crop are the main inputs of LEAP model that produce water requirement satisfaction index (WRSI) which gives yield reduction that helps to predict the number of people affected by the drought (Hoefsloot, 2010). Water balance is the difference between the total amount of rainfall received by the crop and the total loss of water through evapotranspiration (equation 2-1) (Victor et al., 1988).

$$\Delta S = I + P - ETa \qquad \text{Equation 2-1}$$

Where
- ΔS Change in storage
- I irrigation applied (mm)
- P Precipitation (mm)
- ETa actual evapotranspiration (mm)

Rainfall estimation (RFE2.0), Africa rainfall climatology (ARC),Tropical application of Meteorology using satellite data (TAMSAT) satellite and National Meteorological Authority (NMA) rain-gauge stations rainfall archive are the major rainfall input datasets for LEAP standard output (Hoefsloot, 2010).

Rainfall estimation (RFE2.0) image is prepared by NOAA climate prediction centre for USAID Famine Early Warning System (FEWS) and are provided at decadal bases from thermal infrared images from Meteosat, for every 30 minutes the data can be arranged using ground truth data from Global Telecommunication System (GTS) and disseminate through the United states Geological Survey (USGS) (Verdin et al., 2005).

The RFE 2.0 is a combination of three satellite rainfall datasets and one rain gauge rainfall data inputs. The inputs are GOES Precipitation Index (GPI) which is 4 km and half hours of spatial and temporal resolutions respectively, Special sensor microwave imagery (SSN/I) with 15km spatial and 4 times per day (6hr) temporal resolutions and Advanced microwave sounding unit (AMSU) is also 1/3degree (37km) spatial and 5 day temporal resolutions of satellite derived rainfall datasets and the Global Telecommunication Station (rain-gauge) (GTS) is a station rainfall data with uneven spatial and from minute to daily temporal resolutions rainfall data sets (The NOAA Climate Prediction Center, 2001).

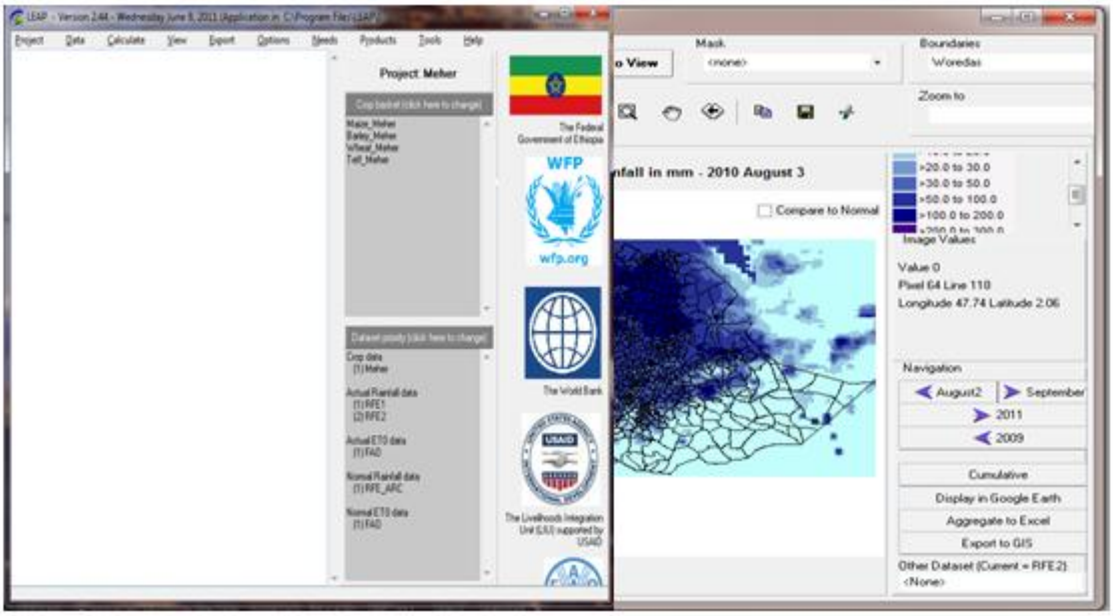

Figure 2-2: LEAP version 2.44

3. STUDY AREA AND DATA COLLECTION

3.1. Study Area

3.1.1. Location and Population

Geographically, the Tigray region is located between latitudes 12°15'N and 14° 57' N and longitude 36° 27' E and 39° 59' E (Figure 3-2). The state of Tigray is situated in the northern part of Ethiopia. According to the new administrative set up, the region is structured into 7 administrative zones these are western, north-western, central, eastern, southern, south-east and Mekelle (the regional capital city) (Figure 3-2). It has 46 wereda (or districts) of which 34 wereda are rural and 12 wereda are classified as urban and mini urban wereda. The total area of Tigray estimated around 53,000 square km, which is 4.82% of the total area of the country. According to Ethiopia central statistics authority (2008) the population of Tigray was 4,314,456 (2008 census) and the projection for the 2011 is 4,803,000 inhabitants of whom 85% of the population lives in rural areas, which depends on rain-fed agriculture. Annual population growth is 2.5%, which is near to at national level.

3.1.2. Climate and Weather

The climate conditions of Tigray vary from arid to semi-arid and are characterized as Kolla (semi-arid), Weyna- dega (warm temperate) and Dega (temperate).The area coverage of the climate sub regions are 53%, 39% and 8% and they have contained low, medium and high rainfall and have high, medium and low temperature respectively (USAID, 2009) and (Bureau Finance and Economic Development, 2007). The rainfall in the Tigray is bi-modal which contains Meher (Kiremet) and Belg seasons and the average annual rainfall of the region ranges between 400 mm and 700 mm and about 84% of the annual rainfall is received during the Meher or main rain season (Gebrehiwot et al., 2011). The effective rainy season covers 50 to 60 rain days and lasts from June to August while the dry period covers the months December to April. The average annual temperature of the region ranges from 13.4°c and 28c° in the high land of south west and western low lands respectively (Gebrehiwot et al., 2011). The Belg rainy season is observed in only a small part of the region and occurs from March to May (Kiros et al., 2009).

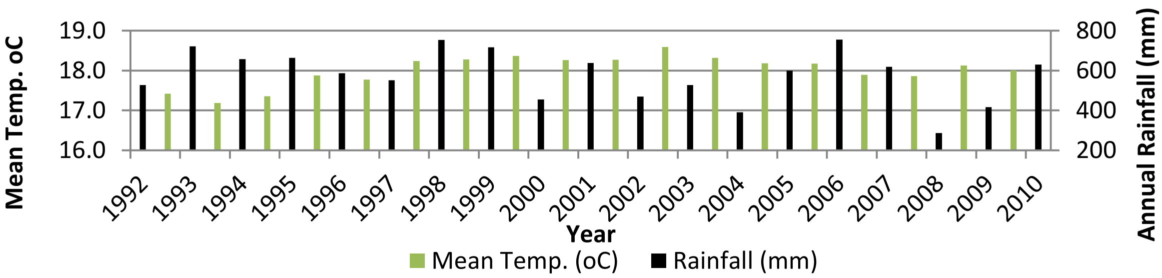

Figure 3-1: Time series of annual rainfall and mean temperature for Mekelle airport weather station (1992-2010).

The average annual rainfall for the period 1992- 2010 for Mekelle airport weather station is 567.1mm.

3.1.3. Relief and Topography

Topography of the region has been shaped by geomorphology processes and by centuries of natural geological erosion and more recently by man-made soil erosion, deforestation and overgrazing. The elevation of the region lies between 600 - 2700 m.a.s.l. The region has pronounced reliefs and many mountain areas represented as cliffs. Many sequences of steep hills and valleys are some of the important physical features of the region. The topography of Tigray contains the three main traditional physiographic divisions Ethiopia: the kola - lowlands (1400 - 1800 meters above sea level) with relatively low rainfall and high temperatures; the Woina dega – middle highlands (1800 - 2400 m.a.s.l.) with medium rainfall and medium temperatures; Dega - or highlands (2400 - 3400 m.a.s.l.) with somewhat higher rainfall and cooler temperatures (USAID, 2009).

3.1.4. Agro-ecological zones and Farming system

Tigray presents a diversification of agro-ecological zones and each agro-ecology is characterised as a function of soils, geology, vegetation, local climate and other natural resources. Mixed farming (crop and livestock) is the dominant system in the region. Both crop and livestock productions are the main sources of livelihood of the dominant rural populations. According to Tigray Bureau of Agriculture and Rural Development (2010) report, the total cultivated land of the region is 13,549.1 square km. Rain-fed agriculture is dominant in the region but currently the irrigation coverage of the region is improving through time. To ensure food security in a variable, drought-prone environment, households try to maximize the productivity (full package) . Barley, wheat, teff, sorghum and maize are the dominant crops growing in the region.

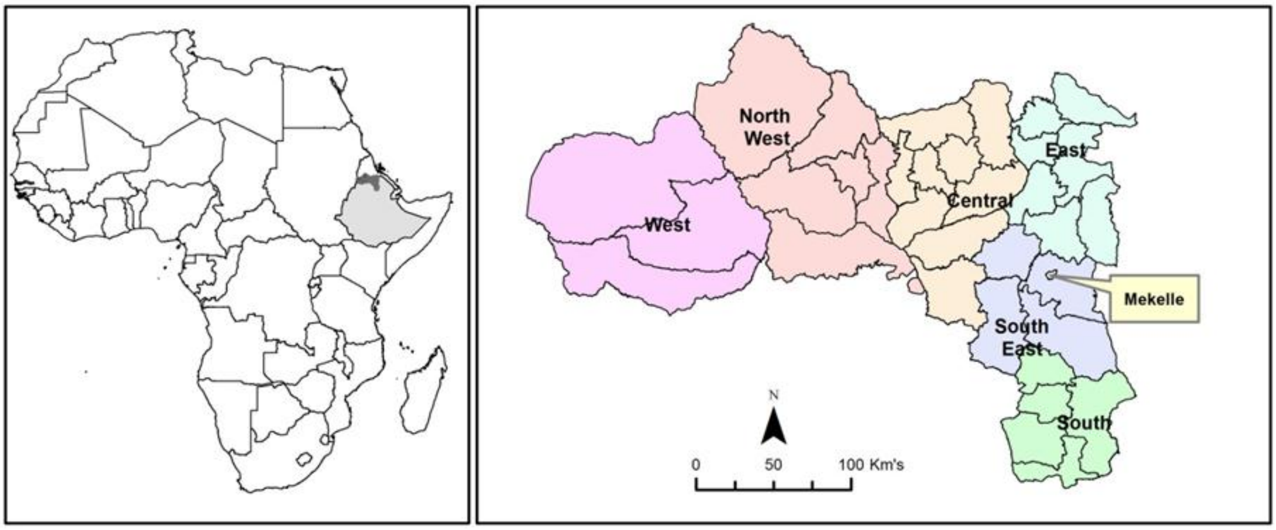

Figure 3-2: Location map of the study area Tigray, Ethiopia

3.2. Data Collection

3.2.1. In-situ Meteorological Data

Meteorological data was collected from Tigray Meteorology Branch Office (TMBO) and National Meteorological Agency (NMA). From 14 first class "A" data was collected while rainfall data was collected from other additional four weather stations, which are classified as third class weather stations. Five year of daily observations were obtained for the period 2006 to 2010.

Tigray region has a rather sparse weather station network with poor areal coverage. Also there is a lack of skilled manpower to collect data and timely report especially in areas which are not easily accessible. The network of the 18 weather stations used in this study is shown (Figure 5-1). Geographic position of the points and the rank of each weather station indicated (Table 3-1).

Table 3-1: Tigray 18 weather stations locations

Ser.no	Zone	Wereda	Station name	latitude	longitude	Altitude	Rank
1	Eastern	Ganta Afeshum	Adigrat	14.28	39.45	2509	1st
2	Central	Adwa	Adwa	14.18	38.88	1927	1st
3	Central	Laelay Maychew	Axum	13.99	38.82	1114	1st
4	Southern	Raya Azebo	Chercher	12.54	39.77	1717	1st
5	Eastern	Atsbi Wenberta	Atsbi	13.88	39.74	2511	1st
6	Southern	Enda mehoni	Maichew	12.78	39.53	2402	1st
7	North western	Tselemti	Maitsebri	13.59	38.15	1349	1st
8	Eastern	Saesie Tsaedaemba	Senkata	14.07	39.57	2269	1st
9	North western	Tahtay Adiyabo	Sheraro	14.39	37.76	998	1st
10	North western	Tahtay Koraro	Shire	14.10	38.30	1732	1st
11	South East	Enderta	Mekelle(ap)	13.47	39.53	2221	1st
12	South East	Enderata	Mekele(obs)	13.52	39.47	2001	1st
13	South East	Hintallo Wejerat	Adi-gudom	13.25	39.51	2107	3rd
14	Western	Kafita Humera	Humera	14.28	36.60	429	1st
15	central	Werei -Leke	Nebelet	14.10	39.28	1988	1st
16	Western	Kafita Humera	Adigosho	14.17	37.31	1117	3rd
17	North western	Tahtay Adiyabo	Badme	14.72	37.80	1072	3rd
18	Western	Tsegede	Danisha	13.57	36.97	655	3rd

First class "A" stations in this research refers to stations which has all daily meteorological data but third class stations are stations which has only daily rainfall data.

3.2.2. Agricultural crop production statistical data

Wereda (district) for this study refers to the lower level governmental administration. Crop yield data and cultivated land areas for the year 2008 to 2010 for all the districts (wereda's) in region were collected from Tigray Bureau of Agriculture and Rural Development (BoARD).

3.2.3. Satellite datasets from GEONETCast

The main satellite datasets used from GEONETCast and accessible in near real-time (e.g. 30' after observation or similar) were:

- MSGMPE or Meteosat 2 ND Generation Multi-sensor Precipitation Estimate (produced by EUMETSAT);
- TAMSAT
- LandSAF MET or Meteosat Evapotranspiration estimate (produced by the LandSAF Facility)

MSGMPE is a satellite precipitation estimate based on a blending technique or merging of microwave rainfall observation on-board the polar orbiting Defense Meteorological satellite program (DMSP) group of satellites and the geostationary observations of MSG (meteosat-9) and more precisely its thermal band at 10.8 μm, that monitors the top-of cloud temperatures and cold cloud duration. The MSG-MPE images are available in near real-time at a 15-minute resolution and for whole the MSG disk (window) at a 3-km spatial resolution. They are commonly available in grib format and can be directly ingested by the Ilwis. Open GEONETCast Toolbox. At ITC, the 15-minute images (96 scenes per day) are processed to daily sum-products (0015-2400) and made available to students and researchers via the itc-ftp-site in Ilwis format. This rolling archive contains the last 12 months of data, except the days when no 15 minutes data were distributed via EUMETSat, or a data transmission interruption occurred (Maathuis and Mannaerts, 2011).

MSGMPE satellite rainfall was processed at 3-km spatial resolution and at daily time step, using the GEONETCast Toolbox plug-in for the year 2010 and for the five-month period (May to September), totalling 153 daily scenes or images. In this study, the MSGMPE was preferred to other satellite rainfall data, due to its combination of relatively high spatial and temporal resolution.

TAMSAT satellite rainfall data was collected at decadal base at ~4 km spatial resolution for the time of June to September 2010 from 12 images.

LandSAF Meteosat evapotranspiration (MET) daily mean evapotranspiration (DMET), which is an actual evapotranspiration estimate produced by the Land Surface Analysis (LSA-SAF). The MET products are available from the GEONETCast Digital Video Broadcast (DVB) data stream (30 minute intervals) or can be downloaded (DMET daily sum product) from the LandSAF website. For this study, data for the year 2010 starting from 15 July 2010 to November 30 2010 that were obtained freely and processed using Ilwis open GEONETCast plug-in. Data was missing for August 30 and 31 and October 21, 2010 from 136 images.

Beside the 30-minute Evapotranspiration (ET) data available in near real time, the daily mean evapotranspiration (DMET) which is the actual daily evapotranspiration produced by the SAF for Land

Surface Analysis (LSA-SAF) for the year 2010 starting from 15 July were obtained also freely and processed using the Geonetcast-plug –in. Using the GlobCover land cover data (2009), the ETa for five different land cover classes could be evaluated for some sample areas with homogeneous land cover, as described in the GlobCover dataset legend.

3.2.4. Satellite datasets from other sources

3.2.4.1. RFE2.0

Decadal rainfall from RFE2.0 (NOAA Rainfall Estimation) image was obtained for the study area at wereda (district) level from LEAP standard output for the year 2010 at 0.1° (~10 km) spatial resolution. This led to a sample dataset of 15 decadal images for the period.

3.2.4.2. FEWS NET Potential evapotranspiration

Daily potential evapotranspiration (ETo) data was collected from Famine Early Warning system NETWORK (FEWS NET) image is available at 1° spatial resolution and was resample, from 1°(~100 km) to MSG (3 km) original spatial resolution. The daily ETo products were obtained for the study area at wereda (district) level from FEWS NET for the year 2010 starting from 15 July 2010 to November 30, 2010 from 139 images.

3.2.4.3. Glob Cover

Land cover classes were extracted from Glob Cover 2009 dataset is available at 300 m spatial resolution. The study area was masked and the actual evapotranspiration of different land cover classes were collected from MET LandSAF.

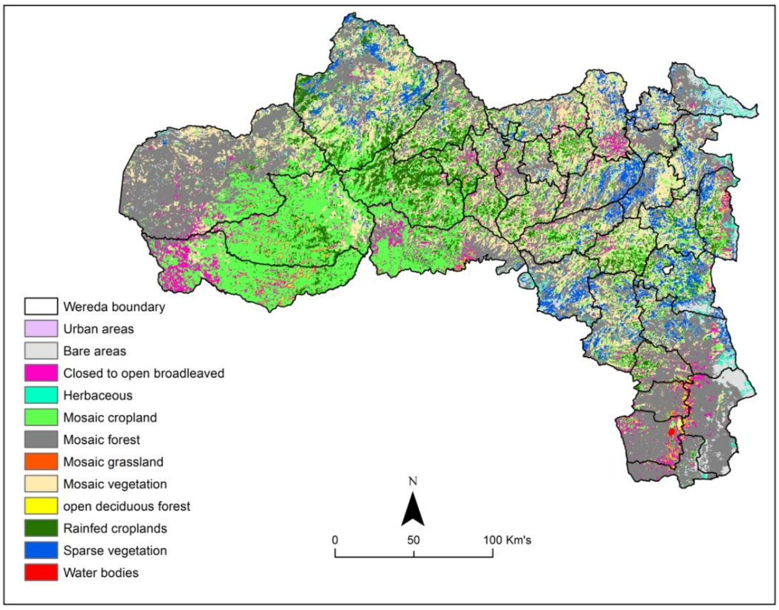

Figure 3-3: Tigray land cover classes map from GlobCover 2009 at 300 meter spatial resolution

3.2.5. Field Data Surveys and Soil measurements

Soil moisture measurements were done during the fieldwork. Some 696 and 24 soil samples were collected from the field using a theta probe and a core sampler respectively. Soil moisture measurement was taken from Hintallo-Wejerat wereda (district) specifically from Adi-gudom plain on September 2011(Figure 3-4).

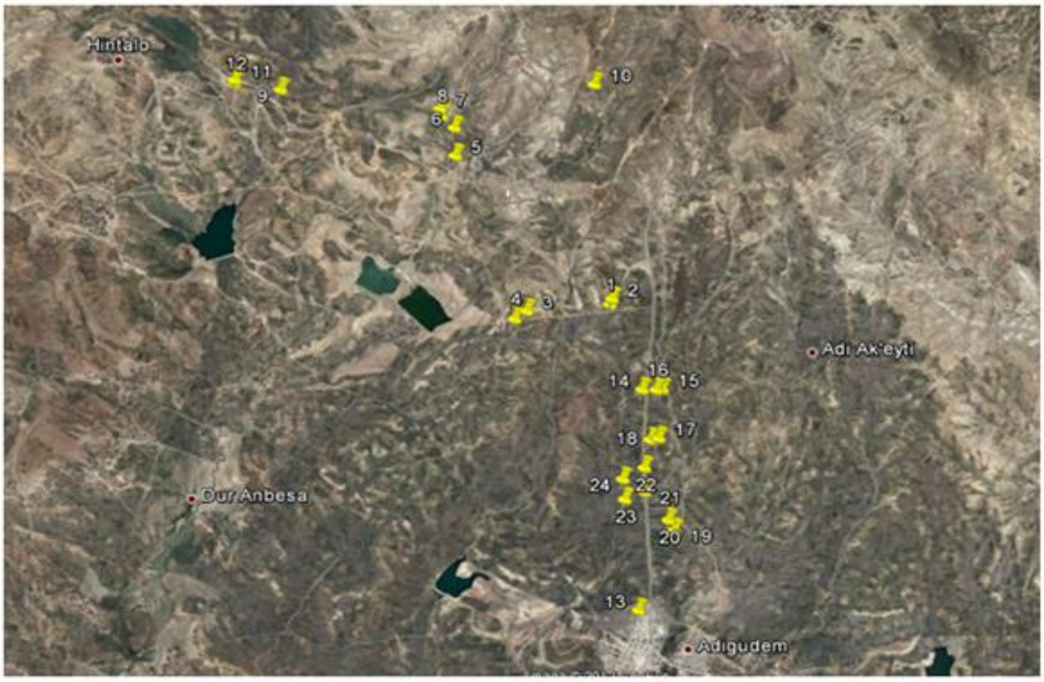

Figure 3-4: Soil moisture sample point locations Adi-gudom plain Tigray, Ethiopia September 2011

4. METHODS

4.1. In-situ Meteorological Data

Rainfall, relative humidity, wind speed, maximum and minimum temperature and solar radiation (sunshine hours) data are available at daily basis from 2006 to 2010 were collected from 14 first class "A" weather stations and moreover rainfall data were also collected from 4 third class weather stations through Tigray Meteorology Branch Office and NMA (Addis Ababa main office). The data was arranged in an Excel spreadsheet.

4.1.1. Reliability of Data

Tigray has a relatively sparse weather station network and there is lack of skilled man power to collect all the meteorological data and to provide timely reports especially in areas, which are remote and/or easily accessible. The rainfall data quality of the stations was evaluated using a double mass curve technique and by using two statistical objective functions namely coefficient of determination (R^2) and root- mean- square error (RMSE).

Double mass curve analysis is a typical hydrological data screening technique of comparing one (each) station cumulative data to a cumulative average of all the other surrounding station data (see Appendix A-1). By line plotting a mass curve, deviations from a straight line indicate a random, accidental or systematic change of values from the station with respect of the surrounding station values, and a closes inspection may be required. The R^2 of the stations were evaluated after preparing the scatter line plot and the RMSE of each weather station was calculated and evaluated. After cross validation of the 18 weather stations, weather stations having a RMSE above 35 mm and with a determination coefficient below 0.5 are marked as problematic. Only 11 stations passed this test and were selected for spatial interpolation and analysis of gauge rainfall. It was obvious that a 7 stations had to be omitted in further rainfall analysis, and further prior data inspection and eventual corrections would be required for these station locations.

4.1.2. Spatial Interpolation using 11 weather stations

The In-situ weather data, provided by NMA and TBMO (2006 to 2010) was available for 18 stations and covered the entire region. In order to generate gridded fields or maps of the weather parameters, a spatial interpolation was made on the data for the period May 01 2010 to September 30 2010 (Figure 5-6) , which is the main rainy season in the study area. Based on the reliability of weather stations the data from eleven stations were arranged on daily basis in the spreadsheet using SPSS16.0 software and then imported into ILWIS using dBase xv format to produce a table. From table operations, a point rainfall map could be created. This point map was then interpolated using a moving average algorithm with an inverse distance weighting (IDW) function available in Ilwis to produce the interpolated raster map with a pixel size 0.1°(~10 km) spatial resolution which is in this case equal to RFE2.0 dataset grid resolution. From raster operations, the interpolated raster map was crossed with the Tigray Wereda raster map to produce crossed table of rainfall at pixel level (see Figure 4-2). Finally, 153 daily rainfall maps were produced from the interpolated rainfall data and using a maplist from maplist calculation to obtain the sum of decadal, monthly and seasonal maps of the region. Equation 4-1, 4-2 and 4-3 shows the mathematical expression of the inverse distance weighting (IDW) function algorithm used in Ilwis. This equation combined with a moving average spatial map filter allows producing a gridded dataset (map) from point dataset.

$$d = D/Do$$ Equation 4-1

Where

d	Relative distance of point to output pixel
D	Euclidean distance of point to output pixel (the distance between two points).
Do	Limiting distance of the point to output pixel

$$IWi = \left(\frac{1}{d^n}\right)^{-1}$$ Equation 4-2

Where

IWi	Inverse weight value for the point i
n	weight exponent (the closer the point the smaller the n value)
d	Relative distance derived from equation 4-1

$$RFI = \sum(IWi \times Vali) / (\sum IWi)$$ Equation 4-3

Where

RFI	Rainfall interpolated mm
IWi	weight value for the point i, derived from equation 4-2
Vali	point value for this case (rainfall in mm) of point i.

4.2. Agricultural crop production statistical data

Yearly crop yield data provided by BoARD was arranged in to Excel spreadsheet. The crop productivity was evaluated using the cultivated land areas of the 34 wereda (district) and the actual yield of 2010. The yield reduction of the three major crops was assessed during the study. The yield reduction was calculated as the ratio of normal yield of the wereda to the actual yield of 2010 for the three major crops namely barley, wheat and teff. In this study, in a wereda where the specified crop is not cultivated and a wereda which has more than 100 percent yield for 2010 reported from BoARD was excluded from the analysis. In four wereda's there is no cultivation of barley such as Kafita Humera, Tahtay Adiyabo, Laelay Adiyabo and Asgede Tsimbla and there are seven wereda's which have no cultivation of wheat i.e. Kafta Humera, Tahtay Adiyabo, Laelay Adiyabo, Mereb Leke, Medebay Zana, Naeder Adet and Tanqua Abergele. Six weredas (Hawzen, Adwa, Tselemti, Tsegede, Welkait and Ofla) reported above 100 percent for wheat yield and five wereda (Tahtay Adiyabo, Laelay Adiyabo, Tahtay Maychew, Welkait and Tselemti) reported above 100 percent for teff yield in 2010.

4.3. GEONETCast Toolbox and Ilwis data processing

4.3.1. MSGMPE

The analysis focuses mainly to compare and to evaluate effectiveness of MSGMPE and RFE2.0 satellite rainfall products for drought early warning and monitoring. Tigray MSGMPE satellite rainfall images were produced by sub mapping the Tigray region from the daily MSG full disk image (covering Africa and Europe and Middle East) using 3 km spatial resolution. Afterwards when needed the map was resampled (to a coarse resolution using a bicubic spline method) to new georeference "leap" having (0° 06' 00.000") or (~10 km spatial resolution and equal to RFE2.0 grid).

To assess how well satellite estimates match to rainfall estimates by the rain gauges, time series are inter-compare principle in the analysis that inter-comparison is for pixels that overlay the actual location of the gauges. Assessment and performance for point rain data was compared with estimate of surrounding 5 pixel and an estimate of surrounding 9 pixels(Figure 4-1).

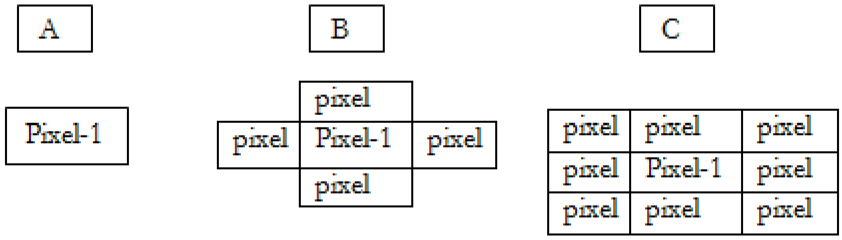

Figure 4-1:Pixel validation of MSGMPE original pixel resolution rainfall estimations 1 pixel (A), 5 pixel (B) and 9 pixel (C)

Case-1: Point-to-pixel accuracy evaluation

Point and wereda aggregated data was collected during the study. The point rainfall data were collected from the point locations by adding the point station to the map. The point rainfall observation data was validated using 5 and 9 surrounding pixels data in order to evaluate the reliability of point data on five stations represented accessible, remote areas and both high land and low land location of the stations. The point data has higher correlation with 5 pixel values than 9 pixel values with an average of 0.997 and 0.996 respectively (Table 4-1), therefore there is good correlation between point and pixel value MSGMPE rainfall estimation it can be possible to use point data for this research.

Table 4-1: Validation of MSGMPE rainfall using R^2 point data based on 5 and 9 surrounding pixel

Station	5 pixel	9 pixel
Mekelle obs	0.998	0.998
Humera	0.999	0.998
Atsibi	0.999	0.998
Axum	0.992	0.99
Chercher	0.999	0.998
average	0.997	0.996

Case-2: Extracted wereda (district) aggregated

For this study the wereda aggregated data refers to the average of aggregated data after extracted from the image, crossed, aggregated, join and grouped by wereda to create daily average aggregated data for each wereda. Rainfall data was collected after joining the rainfall map with the wereda map and grouping the values by wereda. Using raster operations, the Tigray resampled image was crossed to the Tigray wereda map to produce a cross table. The wereda aggregated rainfall table was derived from the crossed table and by grouped and joined the aggregated table daily rainfall was obtained for all the wereda for the period of May to September 2010. Daily rainfall was extracted from 153 MSGMPE images for all weredas found in the region, and decadal, monthly and seasonal rainfall maps for Tigray during May to September 2010 were made (Figure 4-3). The 153 daily images were grouped in a maplist to permit calculations on the image time series like e.g. one final Tigray seasonal rainfall map estimated from MSGMPE.

Scatter plots were used to analyse the correlation between the satellites derived rainfall versus In-situ rainfall at decadal base for all stations and wereda aggregated rainfall data.

Some of the Ilwis commands used during maplist were as follows.

Raster Mapinterpolation=MapKrigingFromRaster('@1',Spherical(0.000,1.000,1000.000),40.00000,p,0,1,16)

Where; @1 is the number of map list that is to be interpolated

Tigraymsgmpeif20100830=Ifundef (Tigrayintpmsgmpe20100830, 0, Tigrayintmsgmpe20100830.mpr)

Tg_mskmsgmpe0509a =iff (mask_Tg=1,?, Tgmsgmpe20100509a)

This command executes a masking of the Tigray region in order to produce a map showing only the Tigray region with data.

The figure below shows how in Ilwis maplist statistics can be used to generate e.g. a sum of a time series of maps

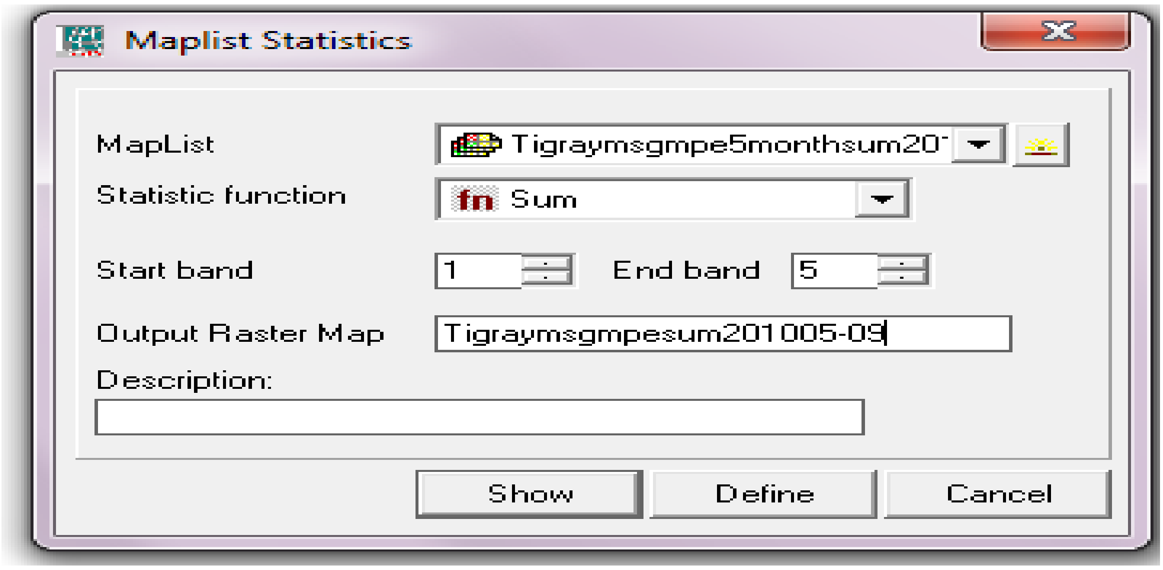

Figure 4-2: Map list statistics sum of rainfall map for 5 months.

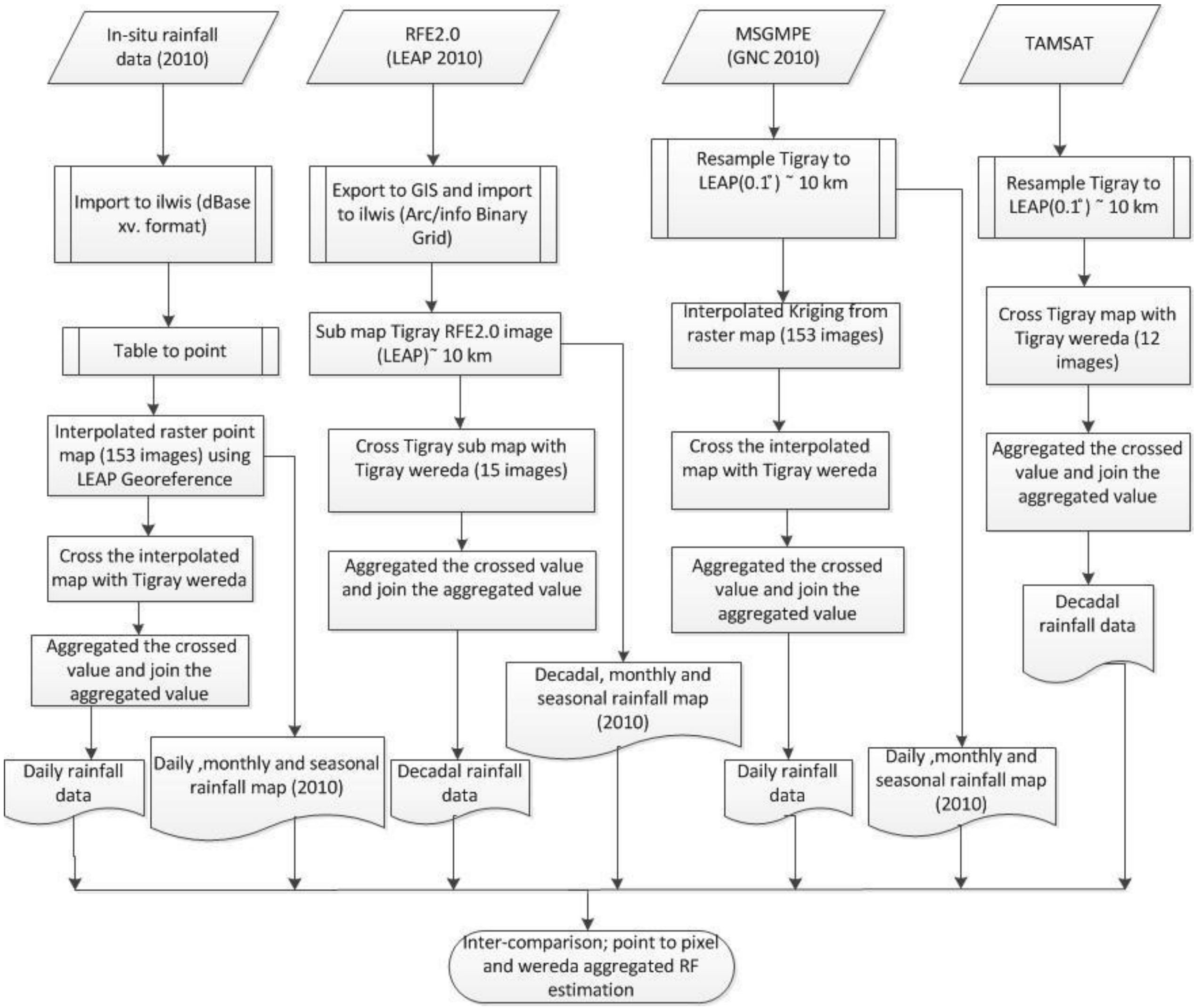

Figure 4-3: Flow chart of rainfall inter-comparison between MSGMP, RFE2.0 and TAMSAT using ground truth data

4.3.2. Daily Mean Evapotranspiration

Daily mean Evapotranspiration (MET LandSAF) is the average daily amount of water evaporation and plant transpiration (i.e. actual evapotranspiration) from the Earth's land surface to the atmosphere. WDMET for this research referes to the Wereda Daily Mean actual EvapoTranspiration data after crossed, aggregated, join and grouped the value extracted from the image. Tigray WDMET images were produced using the same procedure of MSGMPE rainfall estimation indicated (Figure 4-3). Tigray WDMET was extracted from 136 LAS-SAF images for all weredas found in the region. Decadal, monthly and seasonal WDMET maps for the study area from July 15 to November 30 2010 were produced from 136 daily images. Three days had missing data (August 30 and 31, 2010 and October 21, 2010) but using the average of the pervious and the next day, the missing data was filled in and as such a total of 139 days for the entire period was obtained. Using maplist calculations, after creation of a maplist and from maplist statistics (Figure 4-3) by summing 139 images one Tigray seasonal WDMET map was produced from satellite data. The DMET product permitted to evaluate evapotranspiration per day, decade, seasonal and also per pixel or per wereda or regional average.

DMET depends on the land cover class, and therefore the performance of the DMET was evaluated on a number of distinct pure pixel land cover sample areas using the GlobCover map land cover 2009 for the Tigray region. The GlobeCover 2009 land cover map was provided by the European Space Agency (ESA) from Medium Resolution Image spectrometer (MERIS) sensor on ENVISAT satellite and has spatial resolution of 300 meter which shows different land cover classes("ESA GlobCover Version 2.3 2009 300m resolution Land Cover Map," 2011) , and is updated on a regular basis (e.g. 2004, 2006, and 2009). The DMET value was evaluated at pixel level by selecting four different land cover classes in three different sample areas. The land cover classes were rain-fed cropland (14), mosaic cropland (20), shrub land cover (110) and bare area (200). The PDMET which is referes to DMET derived from the four land covers classes selected three pixels. PDMET were collected from the selected land cover class and showed to evaluate the results of all land cover class. DMET varies significantly based on land cover class as shown in (Table 5-6). RFDMET for this research refer to only rain-fed the land cover daily mean actual evapotranspiration data from all wereda pixel. For this research the rain-fed crop land cover class was used for evaluating the GNC derived WRSI and YR which has represented as RFDMET.

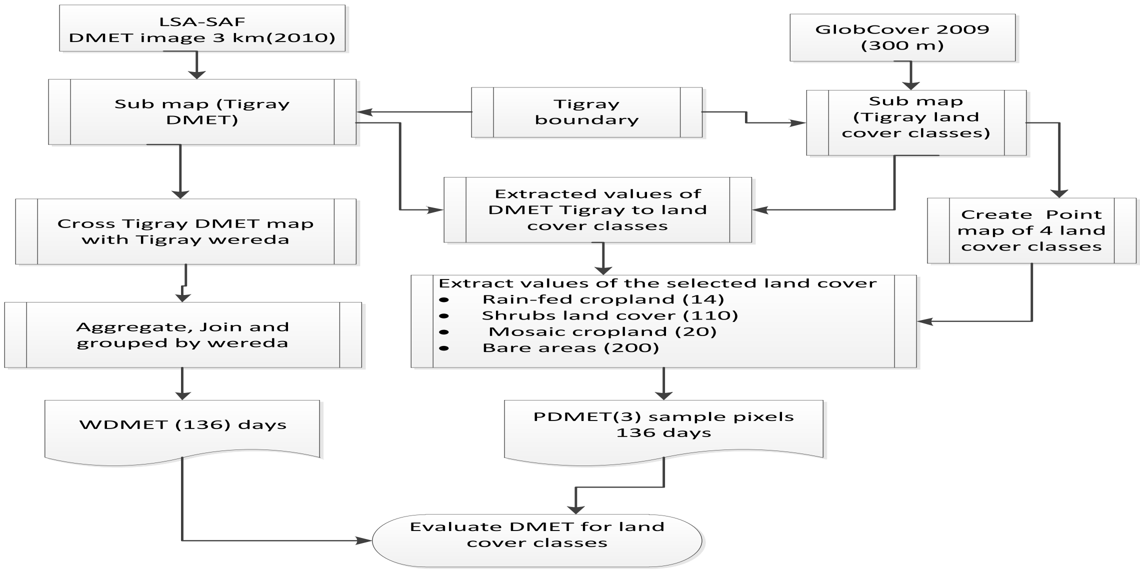

Figure 4-4: DMET derived from different land cover classes

4.4. Satellite data from other sources

4.4.1. RFE2.0: NOAA CPC Rainfall product V.2.0

RFE2.0 is a satellite based rainfall product, produced at CPC (Climate Prediction Centre) of NOAA (USA). It is a merged product containing satellite data with some ground bias control (using gauge data) for Africa and several other region in the world (Senay. G, 2004). It is provided in terms of 10-day (decadal) accumulated rainfall. Currently RFE2.0 is used as rainfall input for LEAP software which is based on a decadal time step and a 0.1° degree or (~10 km) spatial resolution over the study area. The rainfall derived from RFE2.0 was evaluated from May to September 2010.

The 15 decadal RFE2.0 rainfall maps were exported from LEAP to GIS and imported to ILWIS (Integrated Land and Water Information System) using the (GDAL) or Geospatial Data Abstraction Library and using Arc/info Binary grid format. The imported images were sub-mapped for Tigray using also the LEAP Ethiopia regions shape map.

Finally 15 decadal, five monthly and one seasonal Tigray RFE2.0 rainfall map were produced using maplist calculations and statistics in Ilwis. Maps showed to evaluate the spatial distribution of rainfall derived from RFE2.0 during the main rainy season in the study area (Figure 4-3), also the estimation error was evaluated using (equation 4-5).

4.4.2. Famine Early Warning system Network Potential evapotranspiration

Daily Global potential evapotranspiration (ETo) derived from the FEWS project, was collected from the FEWS website at a 1-degree spatial and daily time resolution. These ET values are derived from the global modelled forecast and meteorological observational datasets e.g. GRADS (Grid Analysis and Display System). They are commonly used as inputs for global weather models and forecasting (FEWS NET, 2007). The images after import (GeoTiff) were (resample) for the study area. Using raster operations, the Tigray resampled image was crossed to the Tigray wereda map to produce a cross table. The wereda aggregated rainfall table was derived from the crossed table and by grouped and joined the aggregated table daily potential evapotranspiration (ETo) was obtained for all the wereda for the period of July 15 to November 30, 2010. Based on the formula of WRSI (equation 4-8), this could be used as ETo, normally derived from local meteorological data using penman-Monteith equation.

4.4.3. GlobCover

The GlobCover global land cover dataset 2009 contains different land cover classes at a 300 m ground resolution. This Glob cover dataset was used to confirm pure land cover sample areas and to evaluate the satellite evapotranspiration estimates (DMET) for agricultural land cover and some other land cover classes. Using the Globe land cover the value of actual evapotranspiration derived from GNC was also evaluated. The land cover class were rain-fed cropland (14), mosaic cropland (20), shrub land cover (110) and bare area (200). Only 11 major land cover classes were observed in the study area (Figure 3-.4). The weather-based indices (WRSI and YR) are indeed computed for crop land and therefore ETa from agricultural cropland (RFDMET) should be used as an input to compute the WRSI and YR, when derived from GNC satellite data.

Table 4-2: Spatial and temporal resolution of the dataset used for the study

	Original resolution		Type of	Converted Res.			name
Dataset	Spatial	Temporal	data	Spatial	Temporal	Data	satellite
MSGMPE	3 km	15minute	Rainfall	10 km	10-day	Satellite	EUMETSAT
RFE2.0	~10 km	10-day	Rainfall	10 km	10-day	Gauge and satellite	NOAA
TAMSAT	~4km	10-day	Rainfall	10 km	10-day	Satellite	EUMETSAT
LSA-SAF	3 km	30 minute	DMET	3 km	Seasonal	Satellite	EUMETSAT
FEWS NET	~100 km	Daily	ETo	3 km	Seasonal	Satellite	NOAA
GlobCover	300 m	6 / year	Land cover	300 m	Seasonal	Satellite	ENVISAT
In-situ	Point	Daily	Meteorology	10 km	10- day	Gauge	Ground
Field data	point		soil moisture	point		Ground	Ground

4.5. Field moisture estimation

During the fieldwork in September 2011, a number of soil moisture measurements were made in the area of wereda Hintallo-wejerat specifically in Adi-gudom (see Figure 4-5) which is supported by theta probe and gravimetric measurements. Aims was to validate the GEONETCast satellite soil moisture estimate from Metop-ASCAT sensor. Theta probes combined with gravimetric methods are applied to extract soil moisture content.

The site was classified in to 12 plots and for each plot 2 core samplers and 60 theta probe were taken. 10 theta probe measurements were taken near to the points of core samples and averaged to take as one result. 19 theta probe measurements were also taken separately in the specific site from crop and fallow lands(Figure 4-5). Due to the quick measurement of theta probe, totally 696 samples were taken. The 2 higher and 2 lower from 20 theta -probe measurements of each core sampler were excluded from the analysis. In total, 24 samples were collected using the core sampler to apply the gravimetric method of measurement. The core sampler data was dried using an oven in Mekelle University (Figure 4-6) and after drying; the moisture content of the soil was determined using equation 4-4.

Some pictures during field work on soil moisture content measurements Chris Mannaerts and. Tom Rientjes 14, 2010 Tigray, Ethiopia Adi-gudom plain.

Figure 4-5: Fieldwork soil moisture measurements using theta probe and gravimetric method Adi-gudom, Tigray, Ethiopia. September 14, 2011 to 21, 2011.

Figure 4-6: Laboratory soil moisture measurement Soil sample collected from the site by core sampler was dried using in the oven dry in Mekelle University and soil moisture were calculated using the following formula.

$$MC\% = \left(\frac{fresh\ soil\ weight - dry\ soil\ weight}{dry\ soil\ weight}\right) \times 100 \qquad \text{Equation 4-4}$$

Where :- MC% is moisture content percentage

4.6. Statistical evaluation

The comparison of both satellite derived rainfall MSGMPE with RFE2.0 and *In-situ* rainfall data were done using two objective function statistics i.e. root mean square of error (RMSE) and coefficient of determination (R^2). In addition, the weather–based drought indices, WRSI and YR, derived from GEONETCast data and LEAP output of all the districts were evaluated and compared based on the root mean square of error (RMSE) using the statistical crop data obtained from the BoARD (equation 4-5). There are many statistical methods used for validation and accuracy measurement, like RMSE (Root Mean Square Error), MAE (Mean Absolute Error), ME (Mean Error), Bias, LCC (Linear correlation coefficient) and Eff (efficient score) are some of them. However, RMSE is widely adopted and easily to understand for the users therefore in this research the output data sets between the two satellite products were evaluated with ground truth rainfall using the two objective functions RMSE and R^2. The RMSE is an indicator of how far an average the error from zero (equation 4-5) and R^2 or the coefficient of determination is indicator of the correlation coefficient between the two rainfall datasets. It strictly explains the degree (or %) of variation in a dataset, which can be explained, by the second dataset and its range is 0 to 1.

The inter-comparison of the two satellite rainfall estimations with In-situ data was made using two objective functions for the same decade in the year 2010. The RMSE and the R^2 for the 15 decades for the selected 11 stations were used from point (station) to satellite pixel for computation of the station statistics. By taking the average of 5 and 9 surrounding station pixel 3x3 windows of 3 km pixels for MSGMPE (Figure 4-1) and approximating the 0.1°degree (~10 km) spatial resolution of RFE2.0 respectively.

A small remark is that there are formally two rainy seasons in the region, Meher (Kiremt) and Belg. Since Meher is the main rainy season of the Tigray region, which extends from June to September eventually the second small rainy season Belg was not taken in to account for the inter-comparison of satellite rainfall estimations for this analysis. The agricultural production achieved during the Belg season in Tigray is also much localized near the southeast and of less importance in the regional total agricultural production figures.
Yield reduction (YR) estimation derived from GNC and LEAP standard output was made using the root mean square error for the three major crops growing in the study area (Equation 4-5).

The RMSE used for rainfall and yield reduction(YR) comparison

$$RMSE = \sqrt{\frac{\sum_{i=1}^{N}(Si - Gi)^2}{N}}$$ Equation 4-5

Where	RMSE	Root Mean Square Error
	Si	Satellite derived data
	Gi	Ground based data
	N	Number of the samples

4.7. Water Requirement Satisfaction Index and Yield Reduction

4.7.1. LEAP: Satellite rainfall-based WRSI and YR indices

The LEAP program evaluates the WRSI and YR indices using standard soil water balancing techniques and crop water requirement and evapotranspiration calculations (Hoefsloot, 2010). The WRSI and YR indices obtained from LEAP can be viewed per region or wereda and extracted to an image or a table. Decadal long-term normal reference evapotranspiration (FAO ETo) was used for the computations. The ETa derived from LEAP water balance evaluation depends on the crop type and soil. In the LEAP settings, the soil water holding capacities were set to 100 mm. LEAP calculates ETa based on Penman-Monteith equation and data from the NMA meteorological office and uses the water balance formula to evaluate soil moisture and to evaluate crop water stress.

$$SWit = \text{SWit} - 1 + PPTit - ETa$$ Equation 4-6

Where	$SWit$	soil water at the time t (decade)
	$Swit\text{-}1$	soil water in the previous time step decade
	PPTt	precipitation
	ETa	actual evapotranspiration

The LEAP standard outputs were generated for three main crops grown in the region: barley, wheat and teff. LEAP generated wereda-level WRSI and YR indices. The yield reduction of LEAP is calculated based on the general equation of YR (see equation 4-10). LEAP uses the following classification of WRSI as water stress index (Table 4-2).

Table 4-3: Water Requirement Satisfaction Index (WRSI) in fraction currently used by LEAP.

Ser.no	*Final index (seasonal) WRSI in fraction	
1	> 0 to 50	Complete failure
2	> 50 to 60	Poor
3	> 60 to 80	Mediocre
4	> 80 to 90	Average
5	> 90 to 95	Good
6	> 95 to 100	Very Good

*Final index WRSI refers to seasonal WRSI

Sources(Hoefsloot, 2010) WRSI classification used by LEAP.

4.7.2. GEONETCast satellite ET-based WRSI and YR indices

ETo for this research is referes the FAO definition. Using GEONETCast satellite datasets, the WRSI and YR indices were calculated using the ETo estimates based on NMA meteorological station data or FEWS NET global ETo (potential evapotranspiration) data and the satellite derived actual evapotranspiration (ETa) using RFDMET data. The indices derived from GNC were calculated using the general formula of WRSI and YR (equation 4-8 and equation 4-10) respectively. Another possible method using GEONETCast data i.e., performing full soil water balance calculations using satellite rainfall data and soil data was not implemented, due to time constraints for this MSc.

The first part of WRSI and YR derived GNC was based on input parameters of ETo from FAO Penman-Monteith and it was calculated for 13 stations having complete meteorological data, one station (Maitsbri) from 14 first class "A" has no complete data (equation 4-7). After calculation of the ETo at station level, the station data was imported to Ilwis. The imported station location and ETo data table was then rasterized using a moving average method from point interpolation and inverse distance weighting function. The interpolated ETo map was crossed with Tigray wereda to obtain the cross table of ETo values and finally the crossed table was aggregated and grouped by wereda level to obtain the daily spatially interpolated ETo values for each wereda of the study area (Figure 4-8).

$$ETo = \frac{0.48\times\Delta(Rn-G)+\gamma\frac{900}{T+273}\times U2\times(es-ea)}{\Delta+\gamma(1+0.34\times u2)}$$ Equation 4-7

Where	ETo	reference evapotranspiration [mm day-1],
	Rn	net radiation at a crop surface [MJ m-2 day-1],
	G	soil heat flux density [MJ m-2 day-1],
	T	mean daily air temperature at 2 m height (°C),
	U2	wind speed at 2 m height [m s-1],
	es	saturation vapour pressure [kpa],
	ea	actual vapour pressure [kPa],
	es-ea	saturation vapour pressure deficit [kpa],
	∇	slope vapour pressure cururve [kpa°c-1],
	γ	psychrometeric constant [kpa °C-1].

The other important parameter to calculate the WRSI is the crop water requirement (WR) which is the total demand of water during the growth period of the crop. This was calculated at daily base for the whole growth period of the crops in all the wereda (Figure 4-8). The WR can be derived from the ETo multiplied by a crop water consumption or kc-factor.

In this study, two methods based on GNC data, were used to evaluate the WR and actual ETa:
- Direct estimation of ETa using RFDMET daily ET data from LandSAF at 3 km resolution
- Use of global daily FEWS NET ETo estimates (1 degree resolution or approx. 80-100 km) and kc-factor approach

Clearly a large difference exists between the spatial resolution of the two datasets and derivation methods. Also these ETa datasets are derived using a very different approach and sources.
When using the ETo from FEWS NET, the daily ETo for each wereda was obtained from the image products after resampling to the study area and downscaled to a 3 km resolution. The daily water requirement (WR) or actual ET was then calculated by multiplying the FEWS NET ETo with the kc value of the selected crop during the growing period (Figure 4-8).

$$\mathrm{WRSI} = \frac{\sum_{i=1}^{n} \mathrm{ETa}}{\sum_{i=1}^{n} \mathrm{WR}} \qquad \text{Equation 4-8}$$

Where WRSI Water Requirement Satisfaction Index
ETa Seasonal accumulated actual evapotranspiration
WR Seasonal accumulated crop water requirement (ETo*Kc) see Figure 4-8.

The following kc values for barley, wheat and teff were used: 0.3, 1.2, and 0.25 for the initial, mid and late growth stages of the crop respectively, which is also adopted by LEAP. Daily water requirements were obtained by multiplying daily ETo values with daily kc value of the crop during the growing period. The derivation of kc values from the tabular kc data as shown in LEAP (Figure 4-7) was done as shown here under, daily kc for the growing season was calculated using the formula below (see equation 4-9).

$$kci = (s * Ni) + kc1 \qquad \text{Equation 4-9}$$

$$S = (\,kcmax - kc1\,)/G \qquad \text{Equation 4-10}$$

Where; S Slope
kci kc value at time i
kcmax The maximum kc value for that growing stage
kc1 kc value for day 1 for that specific growing stage (base crop coefficient)
G The number of growing days for that specific growth stage
Ni Number of days at day i
kcd3 kc value for day 3 for that specific growing stage

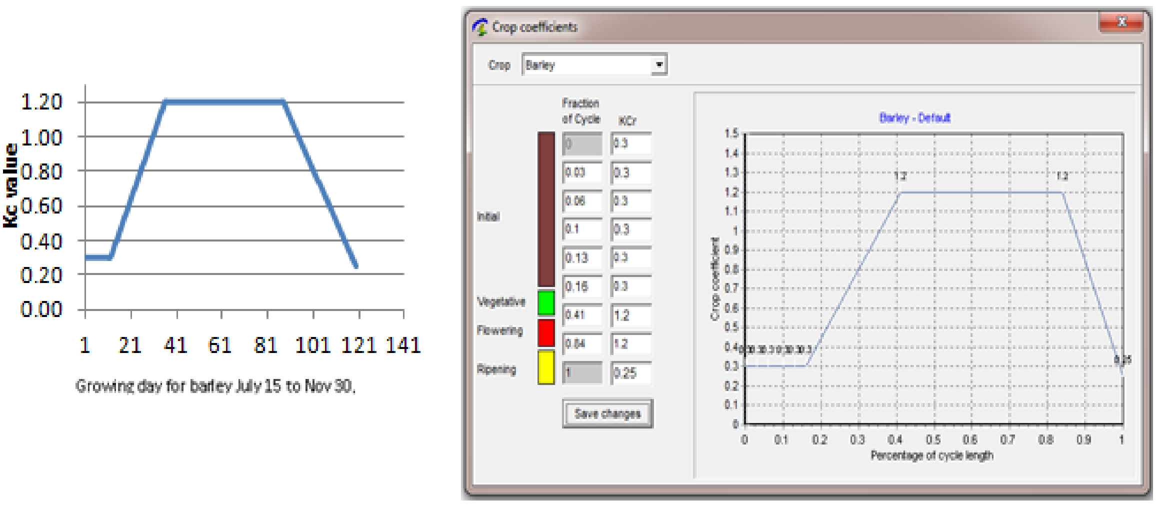

Figure 4-7: Daily and growth period percentage crop coefficient (kc) for barley crop, 2010

Two methods for deriving WRSI and YR indices using GEONETCast DMET data were tested and evaluated. The first method used the wereda aggregated (WDMET) these simply for the day in question and per wereda. This gives an overall average estimate of ETa. The second method took into account the real land cover and land use as derived from recent GlobCover 2009 300 m resolution data. The comparison of ETa derived from wereda aggregated (WDMET) and from the three other land cover classes (PDMET) rain-fed cropland, shrubs, mosaic (mixed land use) and bare land covers were made from July 15, 2010 to November 30, 2010.

Pure rain-fed land cover pixels were selected from all the wereda and found based on field knowledge and inspection of ancillary data sources. The DMET values were extracted for the rain-fed land cover sample areas in a wereda was used as RFDMET estimate (see Figure 4-3).

The point data shows higher correlation with 5 pixel value than 9 pixel values with 0.985 and 0.974 respectively (see Figure 4-1).

Table 4-4: Validation of DMET using R^2 point data based on 5 and 9 pixel data

Station	5 pixel	9 pixel
Mekelle obs	0.994	0.99
Humera	0.999	0.999
Atsibi	0.965	0.943
Axum	0.971	0.941
Chercher	0.997	0.995
Average	0.985	0.974

Water stress and crop yield reduction.

The yield reduction (YR) derived from GNC was calculated using the general formula from water balance output combine with an empirical formula developed by Doorenbosch and Kassam cited by (Hoefsloot, 2010).

$$\text{YR}\ (\%) = 100 - ((1 - \left(1 - \frac{\text{A}}{\text{B}}\right) * \text{ky}) * 100) \qquad \text{Equation 4-11}$$

Where ;- YR (%) yield reduction in percentage
A seasonal actual evapotranspiration of the crop
B seasonal water requirement of the crop
Ky yield response factor of the crop type and the phonological stage of the crop.

Ky depends on the type of crop, for instance sorghum has ky 0.9 and Maize has ky 1.25 so sorghum is more drought resistance than maize. The water stress (ky) factor is a crop dependent variable and its value varies in different literatures but for this study 1.15 ky values which is adopted by LEAP was used for barley, wheat and teff.

4.7.3. Bureau of Agriculture and Rural Development

Crop production data was collected from Tigray Bureau of Agriculture and Rural Development (BoARD). Yield reduction can be defined as the total loss of crop due the availability of water, low soil fertility, pests and disease and agricultural practices of the farmers. However, this research considers that all other factors are taken as constant so the yield reduction was evaluated only based on the availability of water for crop production. In fact, only, a climatic water stress and yield reduction is evaluated. Agricultural yield production obtained from BoARD is the main ground truth data for validation of satellite based yield reduction results derived from GNC and LEAP standard output. It is important to analyse the correlation between wereda statistical yields (and reductions) and satellite derived from GNC RFDMET and LEAP standard output. Figure 4-8 presents the overall structure of the methodology.

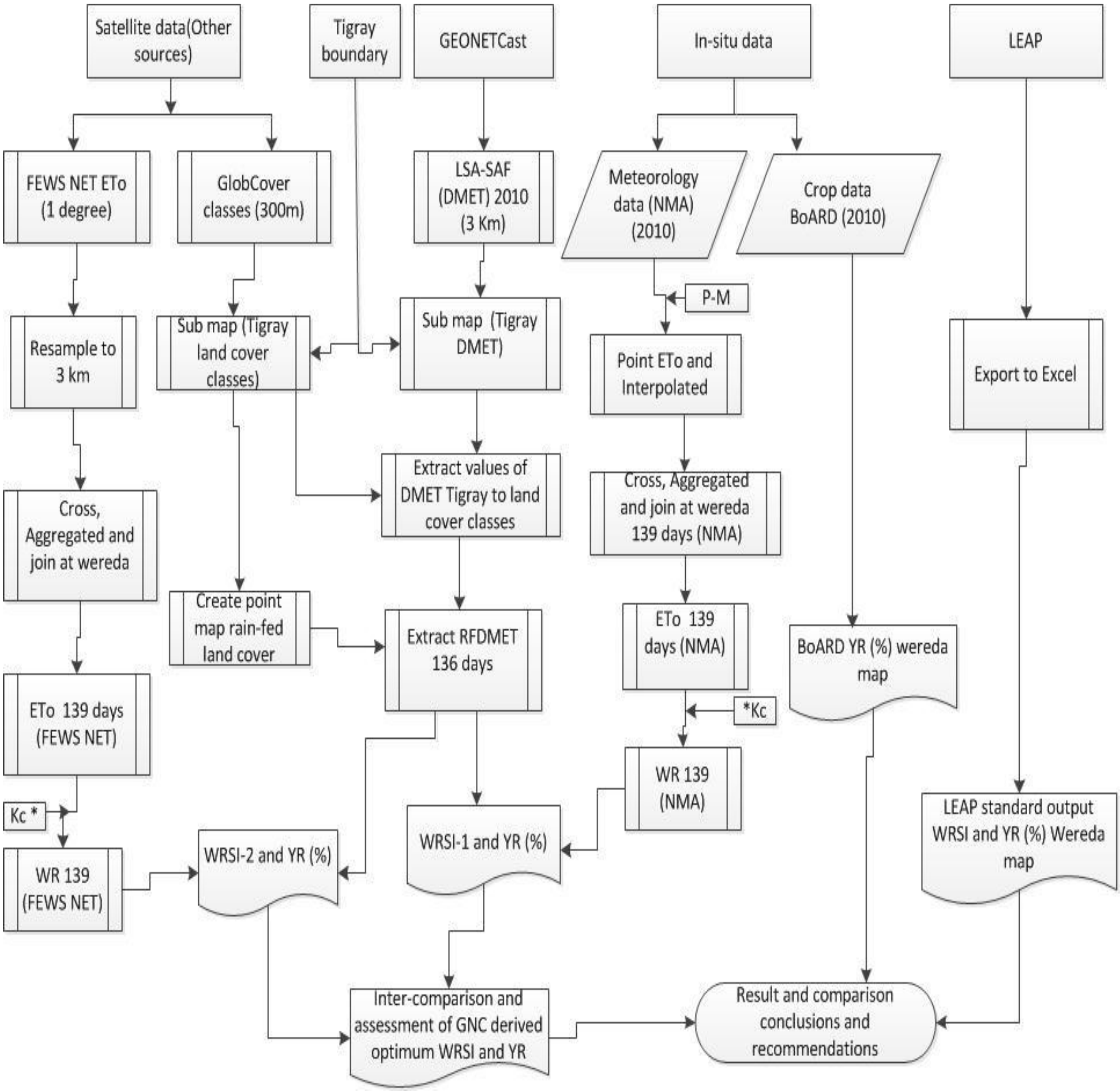

Figure 4-8: Flow chart methodology for, water requirement satisfaction index (WRSI), yield reduction (YR) derived from GEONTCast (GNC) data, Livelihood early assessment protection (LEAP) and In-situ ground truth data

5. RESULTS AND DISCUSSION

5.1. Inter-comparison of rainfall estimations

5.1.1. Reliability analysis of station rainfall data in Tigray

In order to verify the data quality of the rainfall data, all stations used in this study, were evaluated using double mass curves (Appendix A-1). The reliability of 18 stations was evaluated using RMSE and R^2. Only 11 stations gave low (i.e. good) root-mean square error or RMSE and high values of R^2. The reliable stations are: Adigrat, Adwa, Axum, Atsibi, Maichew, Mekelle (ap), Mekell (obs), Adigudom, Nebelet and Badme. The Senkata, Maitsebri, Sheraro, Shire, Humera, Adigushu and Danisha were considered problematic stations (see Figure 5-1). This is maybe due to improper observation, poor accessibility and/or local expertise, or use of poorly or non-calibrated instruments or similar.

Table 5-1: Result of data reliability analysis using double mass curves validations (data year: 2010).

Ser.no	stations	R^2	RMSE
1	Adigrat	0.63	30.6
2	Adwa	0.56	30.32
3	Axum	0.8	15.6
4	Chercher	0.59	34.6
5	Atsbi	0.69	29.6
6	Maichew	0.68	30.5
7	Mekelle(ap)	0.79	20.96
8	Mekele(obs)	0.79	23.18
9	Adigudem	0.75	27.66
10	Nebelet	0.73	29.06
11	Badme	0.67	27.24
12	Senkata	0.36	32.5
13	Maitsebri	0.59	65.7
14	Sheraro	0.16	47.74
15	Shire	0.44	37.64
16	Humera	0.47	26.28
17	Adigoshu	0.37	47.15
18	Danisha	0.002	92.57

Because of this reliability analysis 7 stations are excluded for further analysis and performed for the 11 reliable stations.

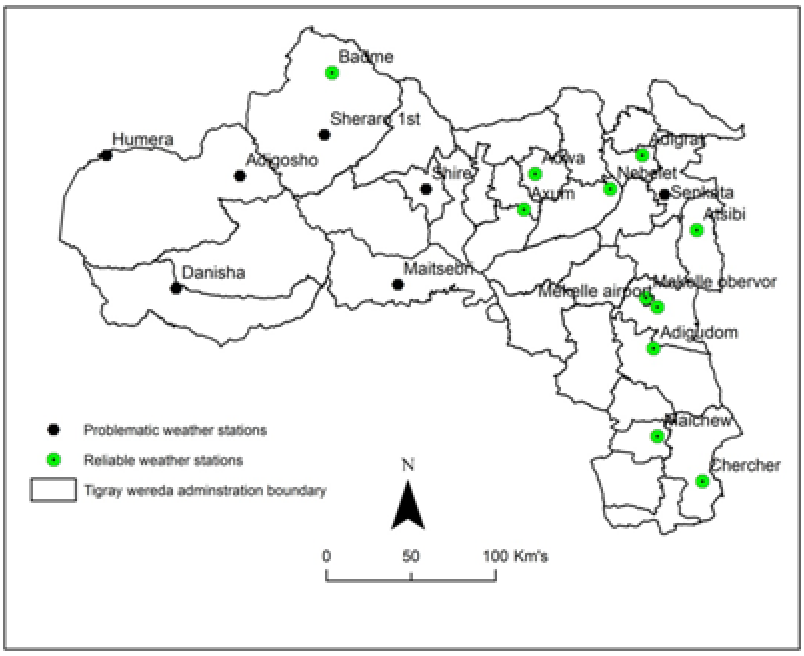

Figure 5-1: Tigray wereda administration boundary and weather stations networks

5.1.1.1. In-situ point to satellite pixel data

Prior to the comparison of In-situ station data to satellite data, tests were conducted a test with a one-pixel window, a 5-pixel window (a 5-pixel cross with the central pixel corresponding to station coordinate), and a 3x3 or 9-pixel window (8 surrounding pixels around the central station pixel) to verify the influence of the satellite pixel selection on the data comparison. If a large local inter-pixel variation is present, selection of a single pixel might affect the point station comparison heavily. The tests conducted is reported in Chapter 4 (Figure 4-1), and indicated that the 1, 5 and 9-pixel window gave similar results. Due to parallax and viewing angle issues of satellite sensor observations, this issue present an important issue in some cases.

5.1.2. In-situ point to satellite pixel inter-comparison

In the first analysis, the two satellite rainfall estimates (RFE2.0 and MSGMPE) were compared to point rainfall observations from gauges of the station network. The inter-comparison focused on two satellite rainfall estimations with In-situ rainfall from gauges and pixel estimates from satellite, in the following comparison will be refereed to as "point to pixel". The comparison was for 11 stations. The inter-comparison was made between MSGMPE and RFE2.0. On average RFE2.0 has high spatial rainfall variability on point to pixel with the value RMSE of 11.96 mm and correlation coefficient of (R^2) 0.90. The MSGMPE product marked a higher estimation accuracy of 6.17 mm RMSE and a 0.98 determination coefficient (R^2) was observed during the period May to September 2010.

The point to pixel inter-comparison in MSGMPE shows good correlation for high and low decadal rainfall. In the RFE2.0 data, there are two outlier values (decades 9 and 10) which decrease the estimation accuracy in this sample data period for this dataset.

Table 5-2: Rainfall inter-comparison point-to-pixel using 11 weather stations at 10 km MSGMPE

Decade	In-situ mm	MSGMPE mm	RFE2.0 mm
1	25.9	20.2	36.7
2	3.9	0.0	5.1
3	0.4	0.0	0.7
4	10.3	6.7	14.4
5	6.5	4.0	9.0
6	9.6	5.4	9.8
7	18.0	13.8	21.6
8	98.5	106.1	88.8
9	72.6	83.8	54.8
10	49.4	41.2	84.9
11	100.0	95.6	103.2
12	96.7	102.2	112.7
13	40.2	46.7	36.3
14	22.4	14.7	27.0
15	10.7	2.5	6.7
Sum	565	542.8	611.8
	RMSE	6.17	11.96
	R^2	0.98	0.9

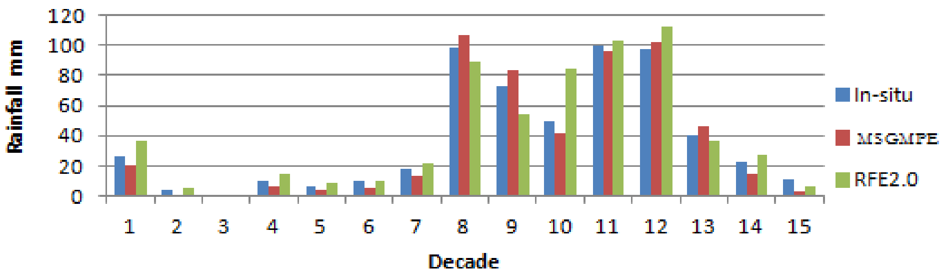

Figure 5-2: Distribution of decadal rainfall depth for 11 point to pixel for MSGMPE and RFE2.0 satellite products and gauged rainfall from May 1st to September 30 2010 (5 months or 15 decades).

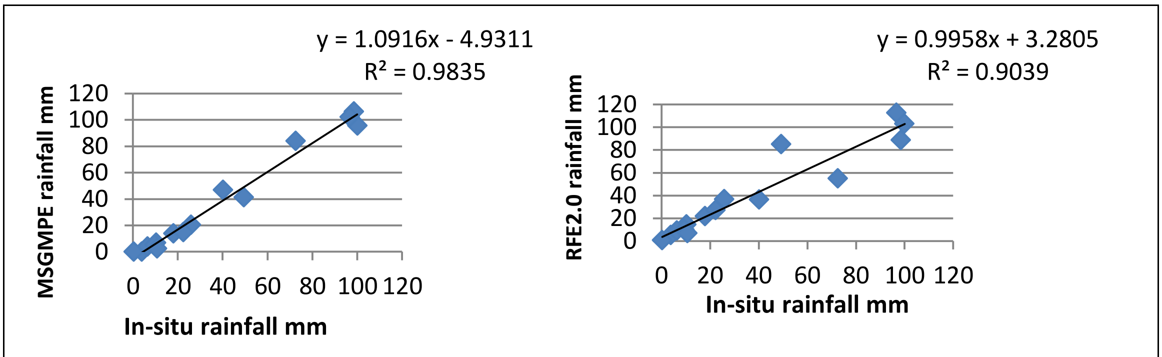

Figure 5-3: Scatter plot of decadal rainfall for satellite products vs. In-situ rainfall at point- to- pixel (May to September 2010) at 10 km pixel spatial resolution

5.1.3. Wereda or district aggregated rainfall estimation

For this research wereda aggregated rainfall data refers the average daily rainfall of the wereda obtained after extracted the image and crossed, aggregated, joined and grouped by wereda. It is important for the authorities to give reliable rainfall estimates for the various districts. Estimates relay on interpolation of station point data and/or pixel-based satellite estimates. Results indicate that RFE2.0 has a slightly higher variability at wereda level as compared to MSGMPE satellite rainfall estimation. It has an estimation error of 14.0 mm with the correlation coefficient of 0.89 using 11 stations for interpolation of In-situ rainfall data over the region of the study area. The MSGMPE has a slightly lower error at wereda level as compared to the RFE2.0 rainfall estimation. The rainfall value at wereda level for MSGMPE has RMSE of 7.0 mm and correlation coefficients (R^2) of 0.98 after resample the study area to 10 km.

Table 5-3: Wereda aggregated rainfall inter-comparison at district (wereda) level, using a spatial resolution of 10 km for both MSGMPE and RFE2.0 (and using 11 reliable ground stations)

Decade	In-situ mm	MSGMPE mm	RFE2.0 mm
1	19.0	23.0	35.4
2	2.1	0.1	3.9
3	1.4	0.0	1.9
4	4.1	7.5	23.2
5	4.6	7.7	17.9
6	9.1	6.9	14.0
7	20.5	18.5	25.9
8	98.5	114.6	90.7
9	75.4	85.2	60.2
10	52.7	41.8	80.9
11	96.7	96.8	112.0
12	92.9	94.5	116.2
13	47.2	49.0	33.4
14	24.5	14.7	26.9
15	8.9	0.8	6.1
SUM	557.5	561.1	648.5
	RMSE	7.0	14.0
	R2	0.98	0.89

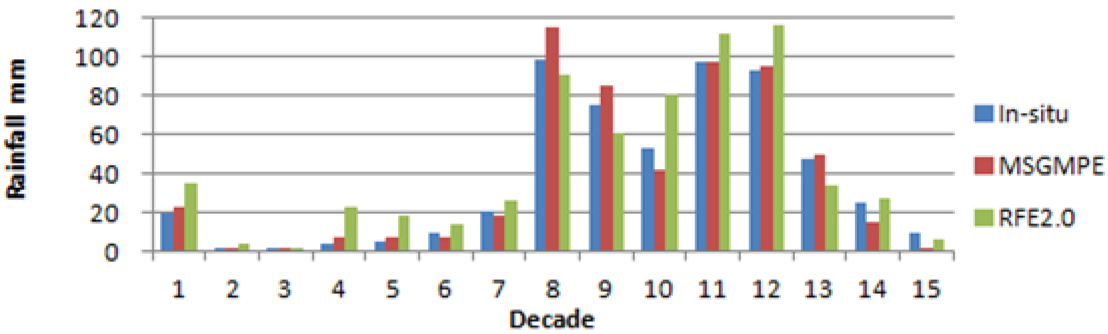

Figure 5-4: Distribution of wereda aggregated (26 wereda) rainfall depths derived from MSGMPE (resamples at 10 km) and RFE2.0 satellite products and In-situ NMA (TMBO) gauged rainfall for 15 decades) May 1st to September 30, 2010

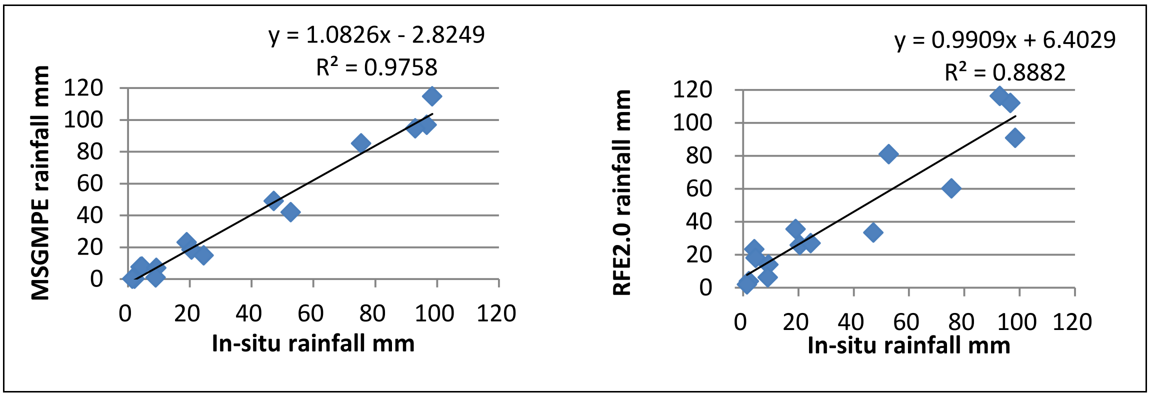

Figure 5-5: Scatter plot of wereda aggregated (26 wereda) rainfall for 15 decades for satellite products vs. In-situ rainfall (May to September 2010) at 10 km spatial resolution.

In this section, RFE2.0 and MSGMPE near real time rainfall estimation evaluated at 10 km spatial resolution of MSGMPE. The plot (Figure 5-5) indicates the relation between the interpolated wereda aggregated In-situ rainfall data versus MSGMPE and RFE2.0 rainfall data. MSGMPE estimates that match to In-situ rainfall (Table 5-3) for only 26 wereda found in Tigray.

For comparison purposes, the MSGMPE satellite data at 3 * 3 km were resampled to coarse resolution scale to match the RFE2.0 LEAP at 10 km resolution in the analysis above. In order to verify the effect of the spatial resolution (and resampling), the comparison of MSGMPE rainfall estimates with the In-situ data was also performed using the original 3-km resolution of the MSG Meteosat data products. The use of the 3-km MSGMPE data for generating wereda aggregated rainfall led only to a very small increase in accuracy (R^2 =0.98 and RMSE = 5.8 mm) as shown also in (Table 5-4).

The inter-comparison was made from single stations at point scale to satellite pixels and wereda aggregated (averaged) rainfall. Only 26 wereda out of 34 wereda in Tigray were evaluated using the two objective functions such as R^2 and RMSE, due to unreliable In-situ rainfall in the western part. The MSGMPE data indicate a slightly higher R^2 and smaller RMSE than the RFE2.0 data in all situations for the period 2010, May to September in Tigray. From the results, a RMSE of 6.17 mm and 11.96 mm and R^2 = 0.98 and R^2 =0.90 was observed for MSGMPE and RFE2.0 respectively for point to pixel using a 10 km resolution. For wereda aggregated rainfall, the inter-comparison gave a RMSE values of 7.0 mm and 14 and R^2 of 0.98 and 0.89 for MSGMPE and RFE2.0 at 10 km spatial resolution of MSGMPE and 5.8 mm RMSE and R^2 =0.98 for MSGMPE was observed at 3 km MSGMPE spatial resolution for the wereda aggregated rainfall estimation (Table 5-4).

Table 5-4: Inter-comparison of wereda aggregated rainfall estimations for 26 wereda May to September 2010.

Objective functions	11 weather station for interpolation				
	point to pixel		wereda aggregate		
	MSGMPE	RFE2.0	MSGMPE		RFE2.0
			3 km	10 km	10 km
RMSE	6.17	11.96	5.8	7.0	14.0
R2	0.98	0.90	0.98	0.98	0.89

In Figure 5-6, the seasonal (15 decades) summer rainfall estimates for eastern Tigray were mapped at a 10 km resolution for the three data sets. The figure clearly shows a fair resemblance of the rainfall. The deviations from the In-situ observations at the two border regions (Northeast (Erob) and south Alamata districts) maybe due to influence of neighbouring or surrounding satellite data, and are not present in the In-situ station dataset. It might therefore well be that the satellite rainfall estimates are at least as confident as the In-situ. It is e.g. impossible or very difficult to obtain In-situ data from the northern border region (Eritrea), whereas satellites give estimates, with the confidence as assessed within the dataset.

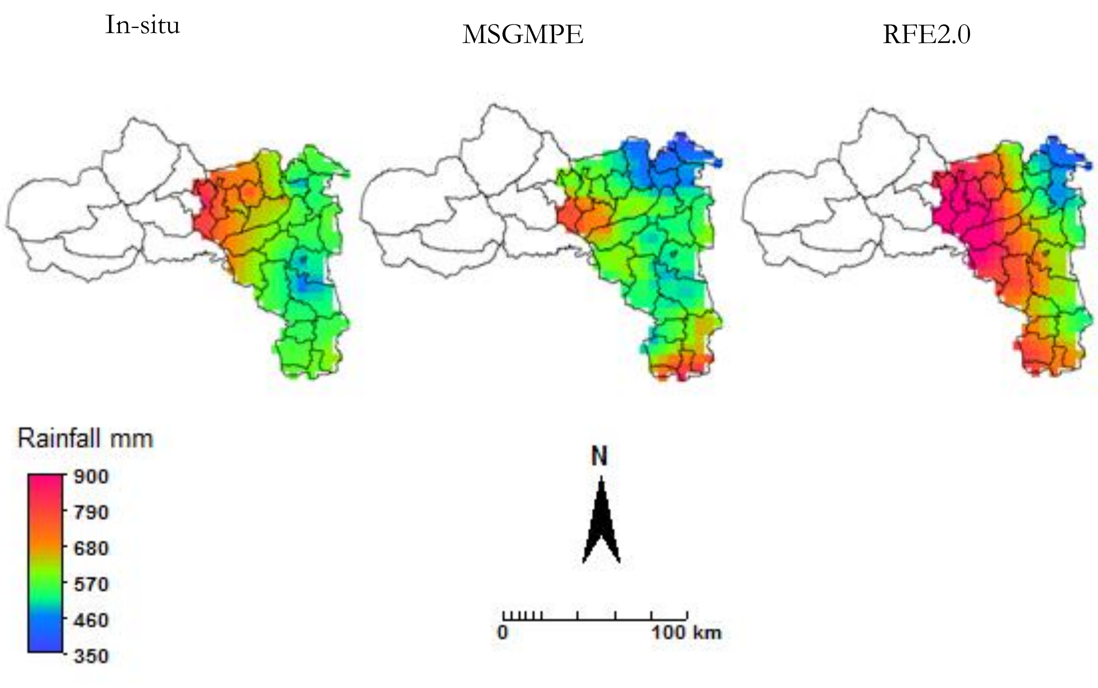

Figure 5-6: Tigray seasonal rainfall estimation maps derived from In-situ, MSGMPE and RFE2.0 at 10 km spatial resolutions (period 2010-05 to 2010-09)

As a last inter-comparison, the MSGMPE and RFE2.0 estimates were also compared to decadal TAMSAT rainfall product, also available on GEONETCast. The TAMSAT estimates also seem quite reliable with similar RMSE and R^2 as the RFE2.0 and MSGMPE products. A slight overestimation of TAMSAT compared to In-situ is observed for this period.

Table 5-5: Wereda aggregated rainfall comparison of east Tigray areal rainfall estimates derived from MSGMPE, RFE2.0 and TAMSAT for the rainfall season period 01-June to 30-September 2010 (4 months or 12 decades).

Decade	In-situ	MSGMPE	RFE2.0	TAMSAT
1	4.1	7.5	23.2	21.6
2	4.6	7.7	17.9	17.9
3	9.1	6.9	14.0	22.2
4	20.5	18.5	25.9	47.7
5	98.5	114.6	90.7	106.5
6	75.4	85.2	60.2	77.7
7	52.7	41.8	80.9	49.6
8	96.7	96.8	112.0	83.2
9	92.9	94.5	116.2	84.5
10	47.2	49.0	33.4	47.8
11	24.5	14.7	26.9	32.6
12	8.9	0.8	6.1	20.0
Sum	535.1	538.0	607.4	611.2
	RMSE	7.5	14.9	12.6

Discussion of rainfall estimation and inter-comparison with In-situ

In the short 5-month summer rainfall period, the MSGMPE estimates give a slightly better correlation with In-situ rainfall data than RFE2.0. As pointed out earlier, RFE2.0 gives poor results for 2 decades (9 and 10), which leads to this bias. (See also Table 5-2 and Table 5-3). RFE2.0 overestimated the two situations, when compared to In-situ, point to pixel rainfall with 8.3% and 16.3% at wereda aggregated (level) based. The MSGMPE data led to a small rainfall underestimation of 4.0% when compared to In-situ point-to-pixel based comparison.

Beyene and Meissner (2010) have compared RFE 1.0 and RFE2.0 with In-situ NMA rainfall. Their finding showed that estimation of rainfall using RFE1.0 and REF2.0 under estimates rainfall, from In-situ data, by 7.0% and 36.0% respectively. In this study, comparison of REF2.0 with In-situ rainfall data overestimated by 8.3% and MSGMPE underestimated with In-situ rainfall by 4.0%. The difference of the result on REF2.0 with Beyene and Meissner (2010) is probably due to differences in topography, climate and the number of weather stations used for comparison and the area coverage of the study. Tigray has rugged topography compared with the other parts of Ethiopia and it receives lower amount of rainfall compared to the whole of Ethiopia. In addition, Beyene and Meissner (2010) have used only three meteorological stations compared to the 11 stations used in this research.

The result at the wereda aggregated rainfall estimates showed that MSGMPE has a slightly better result than RFE2.0. Table 5-4 presents rainfall estimation at wereda level derived from MSGMPE at 10 km and 3 km spatial resolution respectively and RFE2.0 at 10 km. In both tables, the RMSE and the R^2 of the two satellite rainfall estimations are indicated. The average decadal rainfall estimation from MSGMPE, RFE2.0 and TAMSAT also indicates that MSGMPE rainfall estimation is better than the other satellite rainfall estimations as shown in Table 5-5. TAMSAT showed an approximate 14% overestimation of the seasonal values. Of course, only a single rainfall season (4 month) was used as a sample period and more evaluation should be performed to confirm or not these observed findings.

5.2. Comparison of WRSI for major crops derived using LEAP and GEONETCast data

Referring to Chapter 4, the WRSI is an indicator of crop performance based on the availability of water to crop during the growing season (Richard., 1998). It is the ratio of the seasonal accumulated actual evapotranspiration (ETa) to the seasonal accumulated reference crop evapotranspiration or crop water requirement (WR) (equation 4-8).

5.2.1. Livelihood Early Assessment and Protection :Satellite rainfall-based WRSI

LEAP provides standard output of the water requirement satisfaction index (WRSI) at seasonal basis for a certain crop or a crop basket. The data can be obtained at wereda level by aggregation to Excel from the LEAP image viewer output. LEAP calculates WRSI based on the rainfall soil water balance. Therefore, it is a climatic agricultural crop performance index.

For calculating the LEAP WRSI, RFE2.0 rainfall estimates (decadal time step and 10 km spatial resolution), were used in combination with a simple soil water balance evaluator. In LEAP, a standard 100 mm water holding capacity is used for moisture retention by the soil, although this value can be changed for a district. The crop water requirement in LEAP was computed using standard crop coefficients and a Penman-Monteith potential evapotranspiration (ETo) evaluation using interpolated NMA meteorological station data. The WRSI derived from LEAP standard output for barley, wheat and teff in the Tigray region for 2010, was 85.4%, 83.0% and 86.8% respectively. Based on the final index (WRSI) in fraction, which is adopted by LEAP the three crops are classified during this 2010 season in the average WRSI in fraction classes. The WRSI indices for 2010 and for the three crops (barley, wheat and teff) are shown in Figure 5-10.

5.2.2. GEONETCast: satellite ET-based WRSI

WRSI can be estimated using GEONETCast data with different parameters being derived from satellites or combined with meteorological data or model forecasts. Many options exist to compute the WRSI using GEONETCast data, ranging from classic evaluation as done in LEAP based on satellite or In-situ rainfall and soil water balance, but also based on direct (independent from rainfall data) satellite estimates of evapotranspiration as attempted in this study.

In this study, two GNC-based WRSI values were derived and compared:

- WRSI-1: for this WRSI computation, the ETa or the actual crop evapotranspiration was derived from LandSAF or daily Meteosat ET satellite estimates from rain-fed cropland cover class (RFDMET) and the ETo values were derived from NMA station meteorological data using the Penman-Monteith ET model, and spatially interpolated afterwards using the inverse distance weighting technique.

- WRSI-2: for this WRSI computation, the ETa or the actual crop evapotranspiration was also derived from LandSAF or daily Meteosat ET satellite estimates from rain-fed cropland cover class (RFDMET) and the ETo values were obtained using a global near real-time dataset (1 degree daily FEWS-NET ETo values) based on global meteorological forecast models.

The crop water requirement (WR=kc*ETo) was in both cases computed using the same kc factors and seasonal timing (Figure 4-7).

ETo comparison

GNC can estimate WRSI using different parameters based on cumulative ETo and ETa values. This section compares the ETo which were derived from FEWS NET and NMA data using Penman-Monteith. Figure 5-7 shows a comparison of NMA versus FEWSNET daily ETo values for the study area.

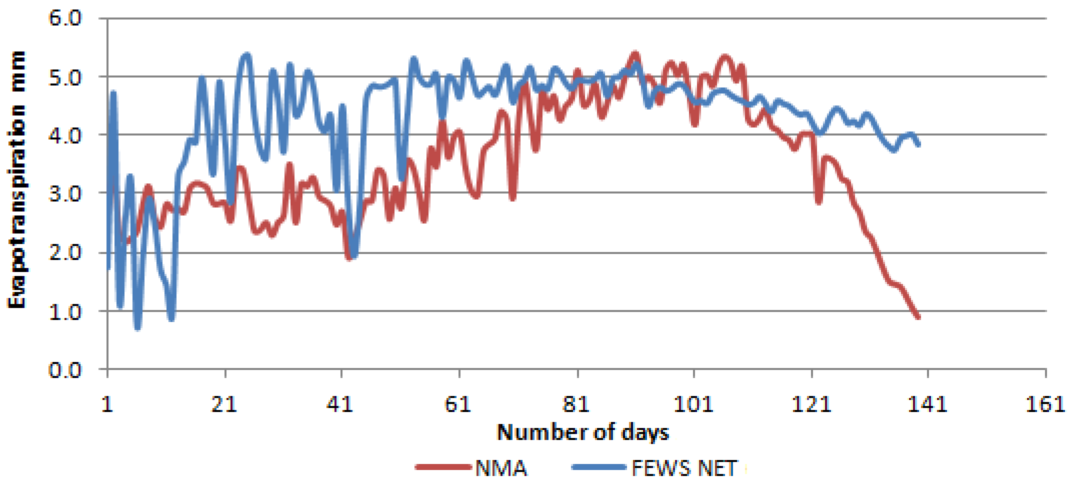

Figure 5-7: Daily potential evapotranspiration (ETo) derived from FEWS NET and NMA meteorological data 2010.

Figure 5-7 shows significant variation between the 2 ETo estimates, especially for the day period 15-70, corresponding to the start of the rainy season. Results of the study suggest may be that FEWS-NET ETo values are more strongly influenced by higher atmospheric conditions (ITCZ or Intertropical convergence zone effects) than the ground based NMA station data ETo.

ETa actual evapotranspiration (DMET) evaluation per land cover

Actual evapotranspiration is largely dependent on land cover properties. The DMET estimates are also computed using a land surface parameterisation scheme and soil-vegetation-atmosphere transfer (SVAT) model, including land cover properties (see Chapter 4 Figure 4-4). The land cover information was used to extract ETa (PDMET) values from different land covers in the region. PDMET in this research refers the ETa value for the three different land cover sample areas. The GlobCover 2009 map together with own In-situ field knowledge and experience in the region was used to identify small homogenous areas for PDMET evaluation per land cover. The WRSI calculation requires ETa estimates from rain-fed cropland (RFDMET). The RFDMET values were then used as input in the GEONETCast WRSI computation.

Table 5-6: Tigray growing season ETa values for different land cover classes and different crop types (139 days, July 15 to Nov 30, 2010).

Land cover classes	Seasonal ETa in mm			number wereda/ pixel
	Average	lower	higher	
RFDMET				
Rain-fed crop land: Barley	285.5	176.9	350.6	30 wereda's
Wheat	288.5	176.9	350.6	27 wereda's
Teff	278.0	153.3	347.6	34 wereda's
PDMET				
Rain-fed cropland (14)	327.0	318.0	339.4	3 pixel
Mosaic cropland (50-70 %) (20)	199.6	202.0	229.3	3 pixel
Shrub land(110)	249.3	312.0	160.5	3 pixel
Bare area (200)	117.9	89.4	154.3	3 pixel
WDMET : wereda aggregated	230.0	116.3	306.3	34 wereda's

The average seasonal RFDMET value for rain-fed cropland cover in the region was 285.5 mm, 288.5 mm and 278 mm for barley, wheat and teff respectively (Table 5-6) from the time July 15 to November 30,2010 .

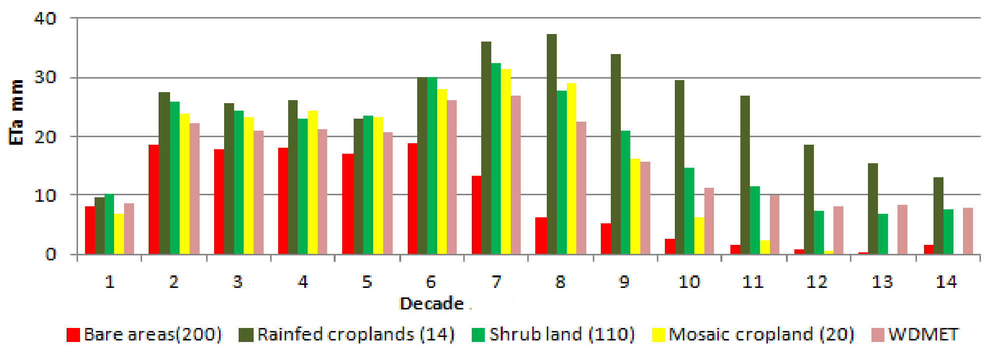

Figure 5-8: Distribution of decadal PDMET from LSA-SAF satellite products for different land cover classes (July 15 to November 2010).

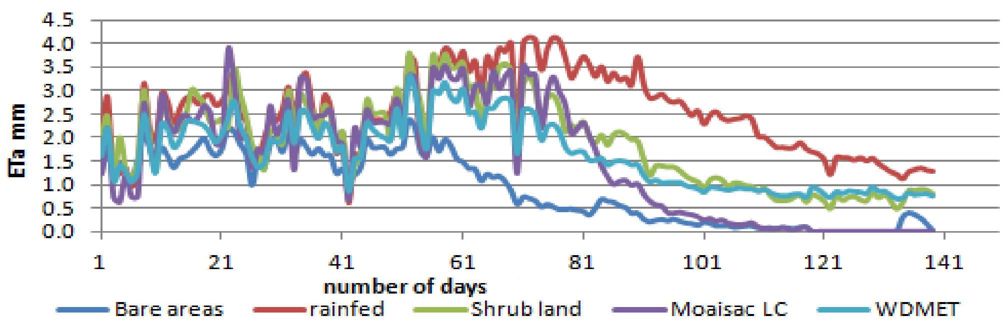

Figure 5-9: Daily PDMET time series from LSA-SAF for different land cover classes derived from known land cover sample areas in Tigray region July,15 to November 30,2010.

At the begin of the rainy season the ETa value for all the land cover classes was increased and there is no high differences between lands cover classes. ETa value for the three land covers is higher during

September (decade 6 to 8) (Figure 5-8) may be due to high temperature (solar radiation), the soil is moist and most of the land is covered by vegetation. The ETa value varies based on land cover classes especially the bare areas has lower ETa value in all the decades ,however the other land cover classes decrease gradually during the end of the rain season.

Satellite ET-based WRSI evaluation

The Table 5-7 shows the comparison of the two GEONETCast based WRSI indices (2) and the classic LEAP WRSI for 3 crop types, Figure 5-10 shows the comparison of WRSI derived from GNC and LEAP.

Table 5-7: Tigray summery WRSI derived from GNC and LEAP for barley, wheat and teff, 2010 using RFDMET GNC 2010.

crop type	WRSI (%)			number of wereda's
	GNC		LEAP	
	WRSI-2	WRSI-1		
Barley	60.0	73.1	85.4	30
Wheat	59.5	72.6	83.0	27
Teff	56.0	69.0	86.8	34
Average	58.5	71.6	85.1	

WRSI-1 estimated at wereda level was 73.1%, 72.6% and 69.0% for barley, wheat and teff respectively, based on LEAP final WRSI in fraction the three crops are classified as mediocre (Figure 5-10 and Table 5-8) and WRSI-2 at wereda level were observed rather low at 60.0% for barley, 59.5% for wheat and 58.5% for teff (Table 5-7). The three crops are classified as poor based on LEAP WRSI classification.

The water requirement (WR) of the crop during the rainy season is small because the crop receives rain but it is high during dry period. Based on the WRSI formula when the WR of the crop increases the value of WRSI becomes low.

The RFDMET under estimated the actual evapotranspiration and may be due to low spatial resolution of GlobCover to estimate DMET for rain-fed cropland cover in Tigray. GlobCover has under estimate the rain-fed crop land cover class (Figure 6-1) and (Table 6 -7) and the RFDMET estimates the average of that pixel as one homogenous pixel value, on top of that the pixel contains mixed land cover classes that affects the RFDMET value of that pixel. In general, Tigray is characterized by mixed land cover (rain-fed crop land, stony, bare land etc. in one pixel) particularly the eastern part of the region is highly mixed small field plots but the satellite consider the average evapotranspiration for that pixel. This causes under estimation of RFDMET value in the study area.

Table 5-8: Wereda classification based on LEAP final index (WRSI) in fraction for the three major crops, 2010

Ser.no	Final index seasonal (WRSI) in fraction based on LEAP classification		Wereda classification based on LEAP final index (WRSI) in fraction					
			GNC derived WRSI			LEAP product WRSI		
			Barley	Wheat	Teff	Barley	Wheat	Teff
1	> 0.0 - 50.0	Complete failure	2	2		-	-	-
2	> 50.0 - 60.0	poor	5	4	4	-	-	-
3	> 60.0 - 80.0	Mediocre	12	9	18	10	9	10
4	> 80.0 - 90.0	Average	9	10	8	9	8	9
5	> 90.0 - 95.0	Good	2	2	-	6	5	6
6	> 95.0 - 100.0	Very Good	-	-	-	5	5	9

WRSI derived from RFDMET GEONETCast and LEAP standard output has different value for different crops. Based on the final WRSI fraction classes adopted by LEAP the wereda of Tigray region for 2010 was evaluated and grouped for the three major crops (Table 5-8).

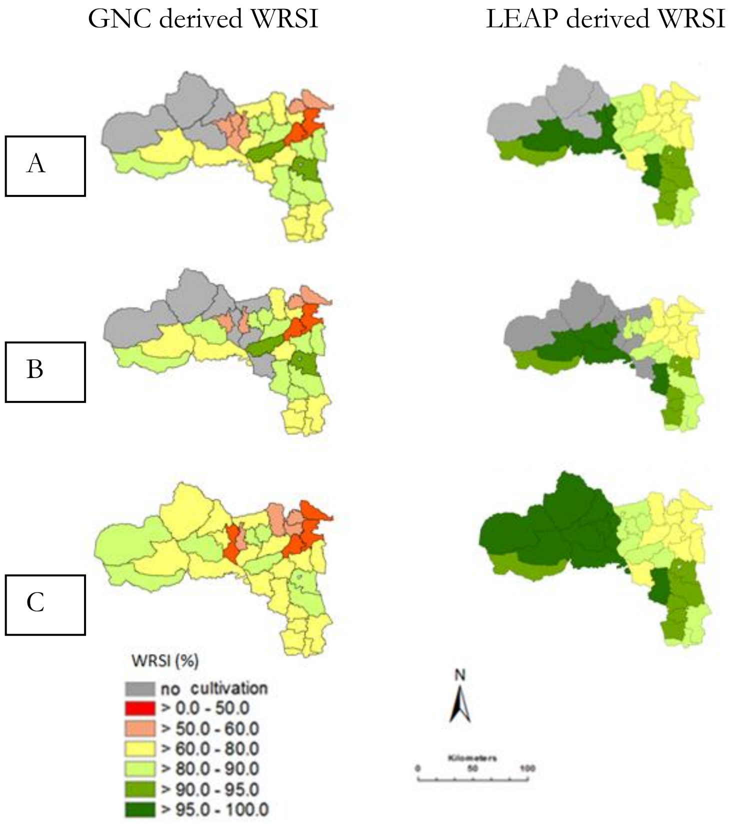

Figure 5-10 : Tigray Water Requirement Satisfaction Index (WRSI) map derived from RFDMET-based GNC and LEAP standard output for barley (A), wheat (B) and teff (C), 2010.

The WDMET under estimated the ETa value presently were only a single average value at wereda level is estimated. such implies that effects of different small value, land covers is ignored. Averaged value for all the land cover classes found in the wereda especially in areas which have less percentage of thus particular rain-fed crop land cause under estimation. Different land cover classes have different value of ETa (Table

5-6 and Figure 5-8). Using the RFDMET value only 30 wereda for barley and 27 wereda for wheat were included in the WRSI analysis the remaining four and seven wereda were not cultivated barley and wheat respectively, during the period 2010 but 34 wereda were evaluated WRSI for teff crop (Figure 5-10).

5.3. Comparison of Yield Reduction estimates derived using LEAP, GEONETCast and BoARD data

Yield reduction is mainly affected by various climatic factors and management practices of the farmer however, this research considers as all factors constant and only evaluated the availability of water for the growing season of the crop. The YR is calculated based on the equation 4-11 adopted by LEAP. The wereda yield reduction map for the three datasets are indicated in Figure 5-11.

5.3.1. Livelihood Early Assessment and Protection– Yield reduction

Livelihood Early Assessment and Protection (LEAP) provides standard output of yield reduction (YR %) at seasonal base for each crop at wereda level based on water balance. YR(%) was observed 15.9%, 17.7% and 15.2% for barley, wheat and teff respectively in 2010 and the average yield reduction derived from LEAP was 16.3%. The average RMSE of yield reduction for the three crop derived from LEAP was 10.9% (Table 5-10).

5.3.2. GEONETCast: satellite ET derived YR

The yield reduction derived from GNC using rain-fed cropland cover daily actual evapotranspiration (RFDMET) was estimated 30.9% for barley, 31.5% for wheat and 35.6% for teff was observed. The average yield reduction derived from GNC was 32.7%. The yield reduction was also evaluated based on the objective function of RMSE, as the report of BoARD is a ground truth yield production data and has an average RMSE for the three crops 8.2% (Table 5-9). The wereda yield reduction map is indicated Figure 5-11.

5.3.3. Bureau of Agriculture and Rural Development yield statistics

The yield reduction in this research was evaluated for 30, 21 and 29 weredas for barley, wheat and teff crops respectively. Wereda Tahtay Adiyabo, Laelay Adiyabo, Kafita Humera and Asegede Tsimbla are not barley growing areas. Wereda Tahtay Adiyabo, Laelay Adiyabo, Kafita Humera, Medebay Zana, Naeder Adet, Mereb Leke and Tanqua Abergele have no cultivated wheat during the study period. Six wereda (Adwa, Hawzen, Welkait, Tselemti, Tsegede and Ofla) for wheat and five wereda (Tahtay Adiyabo, Laelay Adiyabo, Tahitay maychew, Welkait and Tselemti) for teff were reported above 100% yield from BoARD for the year 2010 and those wereda were excluding during the analysis (Appendix Table 6-5 and 6-6).

Table 5-9: Summary of YR comparison derived from GNC, LEAP and BoARD using wereda based cropland cover for the three crops, using the ETo Penman-Monteith 2010.

crop type	YR (%)			RMSE YR (%)		number of wereda
	GNC	LEAP	BoARD	GNC	LEAP	
Barley	30.9	15.9	33.0	2.2	17.1	30
Wheat	31.5	17.7	24.2	6.4	6.5	21
Teff	35.6	15.2	20.1	16.0	4.9	29
Average	32.7	16.3	25.2	8.2	10.9	

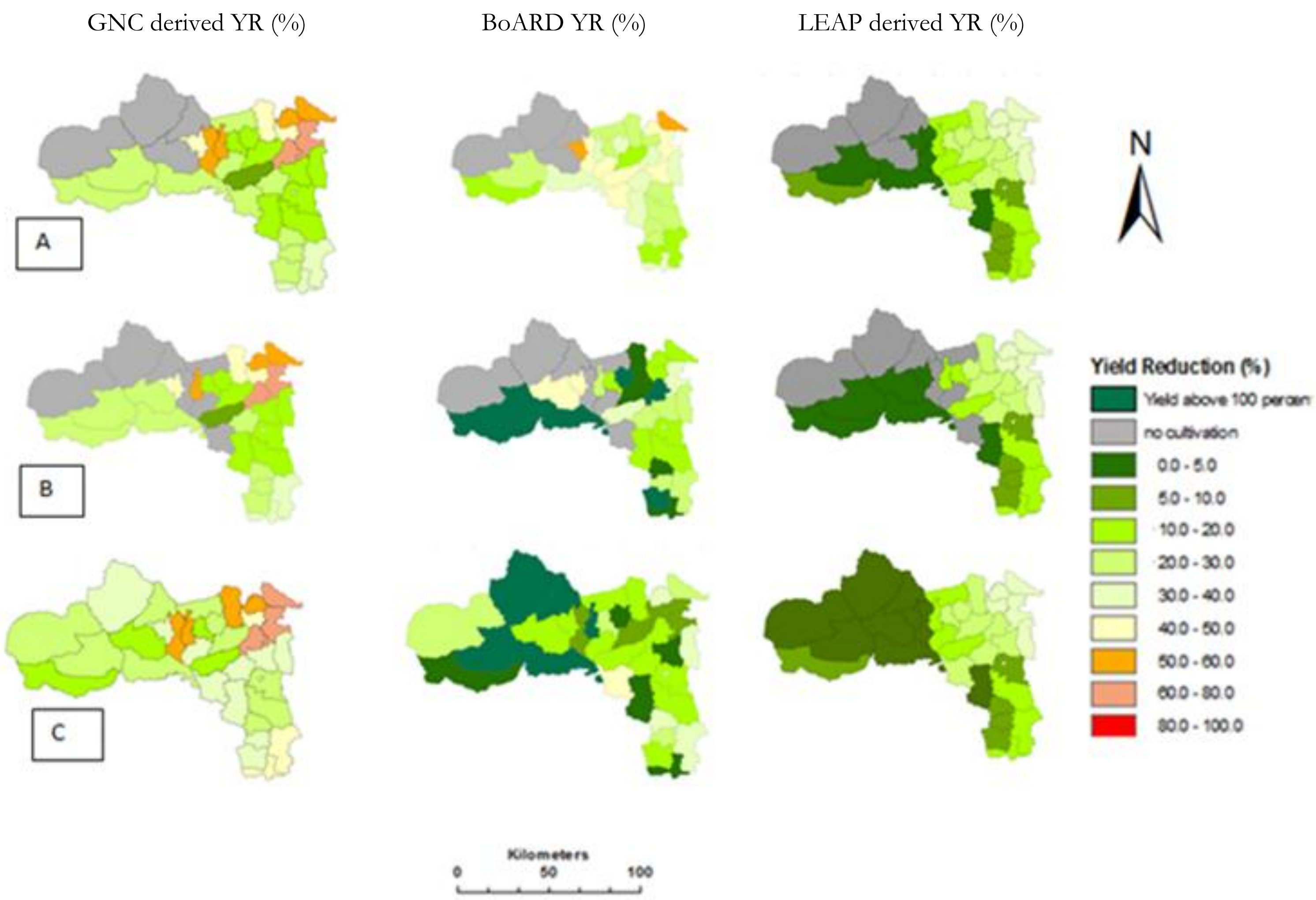

Figure 5-11: Tigray Yield Reduction map derived from RFDMET GNC, BoARD and LEAP standard output for Barley (A), Wheat (B) and Teff (C), 2010

Discussion drought indices

These values show that the WRSI and YR based on merely ETa estimates from GEONETCast satellite data combined with NMA station ETo data (WRSI-1), shows reasonable results for rain-fed cropland (RFDMET) in the Tigray region. This was a first attempt to apply this method and data for this purpose and much refinement is possible. It must be stated that those are original WRSI assessments, purely based on ETa estimation and not using any rainfall information. In this sense, they can present an original and independent evaluation of other rainfall-based WRSI evaluations like the LEAP assessment and others (GEO-WRSI etc.).

DMET depends significantly on the land cover classes as can be expected. Different land covers have different ETa values with the highest ETa values found on rain-fed cropland cover (Figure 5-8 or 5-9). The irrigated area class was almost absent in Tigray at the pixel level. But in areas which have lower percentage of rain-fed cropland cover, per pixel the DMET value have lower values and this affects both WRSI and YR of satellite derived drought indices (Figure 5-10 and 5-11) respectively. On average the drought indices for the three major crops derived from LEAP standard output has 85.1% WRSI and 16.3% YR but GNC based rain-fed cropland cover (RFDMET) has 71.6% WRSI and 32.7% YR and 25.2% yield reduction was reported from BoARD (Table 5-7 and Table 5-9). Yield reduction was also evaluated using RMSE as the BoARD statistics yield is used as ground truth data. The yield reduction RMSE of LEAP standard output is 10.9% and of GNC rain-fed cropland cover is 8.0% was obtained. The GlobCover 2009 data largest mismatch were observed as Tigray BoARD rain-fed cropland area reported in 2010 (Appendix D-1), and cannot be used directly (unsupervised) for giving cropland areas in Tigray and Ethiopia in general.

Important parameters that may affect the results of WRSI and YR are,

1. The daily actual evapotranspiration derived from LSA-SAF DMET and other land cover classes.

2. The potential evapotranspiration derived from FEWS NET, which over estimates ETo compared to NMA based evaluations

3. Availability of rainfall (water) for the crop.

5.4. Soil moisture measurments

The result of the average sample measurements (fallow and crop cover) of soil moisture from the field between theta probe and gravimetric measurement are highly correlated with the coefficient of determination (R2) 0.97(see Appendix E-3).

6. CONCLUSIONS AND RECOMMENDATIONS

Hereafter, the conclusions of this MSc research are presented, with recommendations for future actions related to operationalization of the use of GEONETCast data for food security early warning and further research.
This research had three objectives: i) evaluate the use of GEONETCast near-real time satellite rainfall data using an inter-comparison between other satellite rainfall and In-situ data and ii) derive satellite ET-based drought indices (WRSI, YR) and compare to LEAP standard output and BoARD crop yield statistics data and iii) verify if spatial accuracy and early warning lead time can be improved by using data from GEONETCast.

6.1. Conclusion

6.1.1. Satellite Rainfall estimation

An inter-comparison between rainfall estimated from MSGMPE and RFE2.0 was performed using a five month period that corresponds to the Meher or summer rainfall season of 2010 (May-Sep 2010) in the Tigray region of Northern Ethiopia. The two satellite rainfall estimates were compared and the spatial accuracy was assessed by comparison with ground truth or NMA station rainfall (In-situ) data at decadal basis using 11 weather stations. Those stations are considered reliable based on double mass curve analysis and provided continuous daily rainfall data for the period of May to September 2010. Seven meteorological stations, mostly located in the western part of Tigray had to be discarded due to poor data reliability, as verified using double mass curve station inter comparison. The accuracies and correspondence of satellite estimates with In-situ data were evaluated using 2 indicators that are the root mean square error (RMSE) and the coefficient of determination (R^2).

In a first analysis scenario, station point rainfall to satellite pixel rainfall at the 11 weather stations is compared. Prior to this, that evaluated the pixel geo-location uncertainty or number of surrounding pixels required to sample the station point rainfall. Three pixel windows, a 1-pixel, a 5-pixel cross-window and a 3x3 or 9-pixel window were evaluate (Figure 4-1). The effect of increasing pixel windows was considered minimal, so finally the single point location pixel overlapping the station was used.

The results showed that satellites estimate rainfall with accuracies of 6.17 mm and 11.96 mm RMSE and 0.98 and 0.90 (R^2) coefficients of determination for MSGMPE and RFE2.0 respectively, for the season rainfall totals. In this analysis, the MSGMPE also confirmed to be more accurate (on target or low systematic error, with only random measurement sensing variation), whereas the RFE2.0 indicated some systematic over-estimation error (15%) of the seasonal total, with an equal random error.

In a second rainfall analysis scenario, rainfall data were aggregated to district or wereda level, that is the common spatial unit for food security analysis. The wereda aggregation was done using two spatial resolutions that are 10 km (as RFE2.0) and 3 km (original MSGMPE). Little rainfall difference was found between both pixel resolutions (3 km and 10 km) for wereda aggregated. The NMA point station data were interpolated using an IDW method using the same spatial resolution (3 and 10 km) prior to wereda aggregated.

The TAMSAT decadal rainfall estimate was also compared and gave similar estimations as the RFE2.0 with some overestimation versus In-situ. But, generally a good agreement with the decadal variations is observed.

The following accuracies were derived in the wereda aggregated (wereda-based averaged aggregated) rainfall estimations using 11 In-situ weather stations rainfall interpolated at 10 km and 3 km spatial resolution and compared to MSGMPE and RFE2.0 wereda aggregated. At 10 km resolution RMSE the values of 7.0 mm and 0.98 R^2 were obtained for MSGMPE and 14.0 mm and 0.89 R^2 for RFE2.0 and 5.8 mm RMSE and 0.98 R^2 were obtained for MSGMPE at the original pixel resolution.

The inter-comparison was also made for decadal at 10 km spatial resolution wereda aggregated rainfall derived from MSGMPE, RFE2.0 and TAMSAT for the period July to September 2010. RMSE of 7.5 mm for MSGMPE, 14.9 mm for RFE2.0 and 12.6 mm for TAMSAT was obtained.

This preliminary analysis indicates that MSGMPE provides a slightly better spatial accuracy for rainfall than RFE2.0 (and TAMSAT) at point-to-pixel and at wereda aggregated for the entire period.

More analysis and testing is recommended to verify these findings, as RFE2.0 and TAMSAT are theoretically ground controlled (but not near real-time) and MSGMPE is a direct near real-time satellite estimate. It can however well be, that the ground control and bias correction for RFE2.0 and TAMSAT products is not done in these mountainous regions. MSGMPE might be well suited to capture the type of more convective rainfall occurring in the Meher season in the Tigray region. This rainfall originates from the tropical ITCZ (Inter Tropical Convergence Zone) system migrations at these latitudes in the summer.

6.1.2. Water requirement satisfaction index and Yield reduction

The Water Requirement Satisfaction Index (WRSI%) was calculated using GEONETCast data and LEAP standard output at the wereda level. Three important crops were selected as test cases that are wheat, barley and teff. First, two GEONETCast ET-based WRSI indices were evaluated: a WRSI-1 with ETa based on LSA-SAF RFDMET combined with NMA meteorological station ETo estimates, and second a WRSI-2, with the ET- based on LSA-SAF RFDMET combined global ETo estimates from FEWS NET.

The WRSI indices computed using GEONETCast data were evaluated for rain-fed land cover as aggregated by satellite images, combined with known (own ground thrusting and field experience) agricultural sampling areas in different districts.

The overall WRSI obtained from LEAP processing for 2010 for Tigray region was observed at 85.1% on average for the three crops. The GNC derived and satellite ET-based WRSI-1 led to an estimate of 71.6% for Tigray for the 2010 season, whereas the WRSI-2 (using the global ETo data) lead to a value of 58.5% (Table 5-7).

It is not well know the absolute true value of the WRSI, but only that LEAP represents a rainfall-based and soil water balance computed index, whereas the GEONETCast WRSI are independent, not based on rainfall, but rely only on satellite ETa estimations.

The lower values of the GNC WRSI-1 values can partly be explained by the pixel-based assessment from all the wereda RFDMET (spatial resolution of 3 km), which fundamentally senses field areas, but also other land surface features (rock outcrops and other). The very low values for the WRSI-2 based on RFDMET and FEWS NET ETo can be attributed to the large ETo values obtained from FEWS NET when compared to NMA station ETo. Therefore, this study attempted to judge this method as still not accurate (systematic bias) and cannot recommend the use of this WRSI-2.

The WRSI-1 (satellite ETa from DMET combined with ground meteorological ETo data), underestimates compared to WRSI from LEAP, but this can only be verified with real field observations of crop yields and reductions due to rainfall (crop water supply). However, as shown hereunder with the yield reduction comparison, the use of the WRSI-1 using GEONETCast data seems a good and independent index to compare to the standard WRSI from LEAP.

The YR or yield reduction was therefore also analysed against statistical agricultural crop data from the BoARD of Tigray. The YR comparisons were made to evaluate the reliability of the yield reductions derived from GNC data and LEAP standard output using the statistical crop data of Tigray region obtained from Bureau of Agriculture and Rural Development (BoARD) who were considered here as ground truth data.

The average yield reduction in 2010 for the three major crops analysed and derived from the ET-based WRSI and derived YR% was 32.7%, whereas the LEAP standard output gave a YR of 16.3%, compared to 25.3% from the BoARD data. If the BoARD data are considered as ground truth, then the observation indicates that the GEONETCast based assessment, slightly overestimates the crop yield reduction, and the LEAP underestimates the YR.

The accuracy of the yield reductions for the different wereda's was also evaluated for YR derived using the Geonetcast WRSI-1 and LEAP for the three crops and gave a RMSE of 8.2% for GNC and 10.9% for LEAP standard output (Table 5-10).

One of the major issues to be resolved is the knowledge of land cover areal in the different wereda's. The GLOBCover2009 data set was evaluated for Tigray. GlobCover has 300 m spatial resolution and is not well applicable to estimate rain-fed cropland generally in Tigray region and specifically in the eastern part of the study area, which is very mountainous and highly mixed small field plots. The rain-fed land cover areas obtained from GlobCover did not well match the real (own field working knowledge in several districts) or BoARD statistics on agriculture land. There seems to be a mismatch even with the sum of agricultural and mosaic croplands. Agricultural land is not well representing rain-fed land cover area and it is difficult to use the land cover dataset as basis for rain-fed land areal in the region. The globe cover strongly underestimates the rain-fed land cover of the study area (Appendix D-1).

This research showed that satellite based rainfall and actual evapotranspiration estimation and derivation of satellite (ET-based) drought indices can help us for decision making for drought early warning and monitoring, especially in areas like Tigray where weather stations are sparsely distributed. Drought prone areas require close supervision to monitor droughts, which demands high administration costs for supervision and takes time. Independent satellite estimates can well support field observations.

6.1.3. Spatial resolution and timely prediction

This study has shown that the use of GEONETCast data and especially the rainfall and evapotranspiration rates derived from MSG (EUMETSAT MSGMPE and LSA SAF DMET) permit to improve the spatial resolution and timely prediction of drought indexing. The data are supplied at 3 km spatial resolution and are available in near real time (approximately 30' after imaging). This can improve e.g. LEAP assessment, currently done at a 0.1-degree or ~10 km resolution and at the decadal time step. Using MSGMPE, country wide rainfall fields can be generated in near real time or at a daily time step without problem.

6.2. Recommendations

Especially the current trends in the availability and accessibility of high spatial resolution satellite data can contribute to improve the accuracy of drought early warning and monitoring. Based on the findings of the research the following can be recommended.

- Satellite derived rainfall estimation from MSGMPE can be applied for drought early warning and monitoring in Tigray region for the Meher rainfall season. However further study using additional data and years is needed to confirm this initial findings and may give more insight in these preliminary but promising results in the study area.

- Using GEONETCast ET data (e.g. DMET) to generate rainfall-independent drought indices WRSI and YR, which is very different from the standard procedure (using rainfall and a soil water balance). This method may be a good independent verification tool, but only if further investigations and refinements are made. Doing further in-depth analysis using field evidence, is recommended in order to be able to improve drought early warning and monitoring in the study area. In addition, other satellite ET retrieval methods like the SEBS algorithm and available in Ilwis could be used and evaluated.

- Tigray is characterized by a very mountainous relief and mixed and uneven land covers. The dataset of GlobCover (2009) for rain-fed crop land areal estimation in Tigray region is not well applicable, due to poor ground correspondence with rain-fed land areas. So, further validation of this dataset is recommended in Ethiopia. Further study will be needed and is recommended to improve the land cover area assessment using satellites and ground surveying.

- Further study should be carried out using long term drought years data to evaluate accuracy of GNC derived and LEAP standard output drought indices.

- Due to the limitation of time this research was not implement and compare the full classic method using soil data for estimations of WRSI and YR in the study area further research will be recommended. Also implementing the WRSI method (as in LEAP) using GEONECast data, but including improved soil, topographic and land cover data is recommended.

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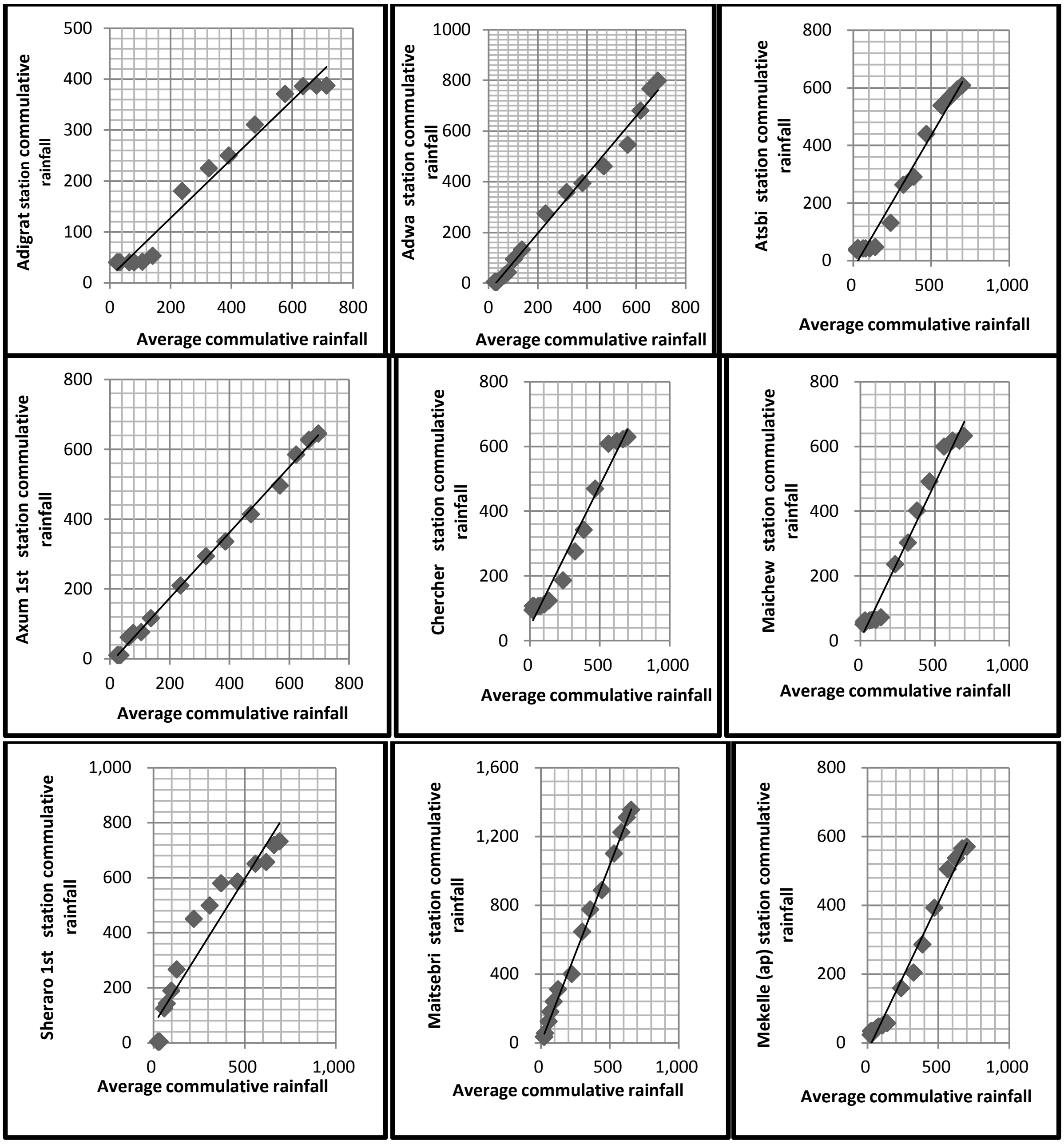
APPENDICES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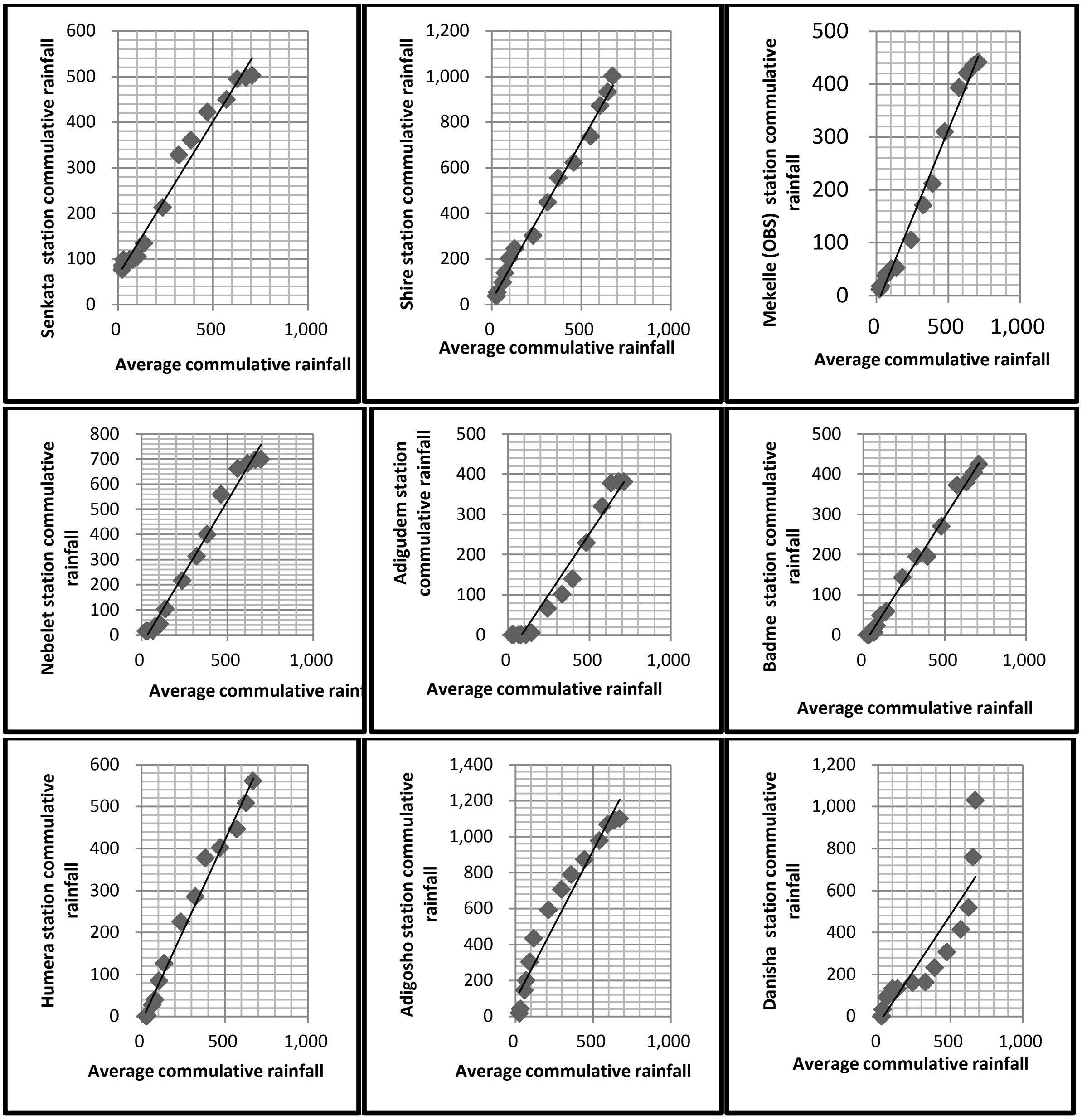


Appendix A 1:Weather station cross validation for rainfall (mm) using Double mass curve for 18 weather stations.

Appendix A 2: Satellite rainfall estimation from MSGMPE and RFE2.0 Point to pixel

Objective function	18 stations		
	MSGMPE		RFE2.0
	3 km	10 km	10 km
RMSE	10.7	10.75	16.4
R^2	0.94	0.93	0.81

Appendix A 3:Seasonal rainfall derived from In-situ, MSGMPE and RFE2.0 for only 26 wereda

ser.no	wereda	In-situ mm	MSGMPE mm	RFE 2.0 mm
1	Erob	532.7	437.5	388.1
2	Ahferom	600.0	469.9	584.9
3	Gulomekeda	523.3	429.7	456.7
4	Mereb Leke	619.9	545.1	747.2
5	Sa/Tsaedaemba	530.9	489.2	441.4
6	Ganta Afeshum	527.3	464.5	480.3
7	Tahtay Maychew	605.9	633.0	910.7
8	Medebay Zana	580.1	672.0	983.1
9	Adwa	681.2	534.7	696.8
10	Laelay Maychew	624.6	604.5	814.4
11	Werei Leke	614.1	578.7	662.2
12	Hawzen	574.7	555.1	545.1
13	Atsbi Wenberta	552.7	568.0	476.9
14	Naeder Adet	587.8	690.5	979.4
15	Wukro	533.3	534.6	557.6
16	Kola Temben	567.5	585.3	805.2
17	Degua Temben	522.9	544.7	656.7
18	Enderta	484.9	522.3	582.0
19	Saharti Samre	510.0	561.6	679.7
20	Hintalo Wejirat	482.0	526.7	552.5
21	Alaje	511.9	535.5	579.9
22	Raya Azebo	557.5	656.4	546.1
23	Endamehoni	532.4	538.3	607.9
24	Ofla	540.0	598.2	704.8
25	Alamata	555.3	726.8	667.4
26	Tanqua Abergele	541.8	591	753
	Average	557.5	561.3	648.5
		RMSE	74	144.5

Appendix B-1: Tigray rain-fed cropland cover classes(RFDMET) estimated from LSA-SAF for the major three crops during the growing season (June 15 to November 30, 2010).

Teff			Barley			Wheat		
No	Wereda	ETa mm	No	Wereda	ETa mm	No	Wereda	ETa mm
1	Tahtay Adiyabo	312.7	1	Erob	203.5	1	Erob	203.5
2	Laelay Adiyabo	299.1	2	Ahferom	228.2	2	Ahferom	228.2
3	Erob	188.2	3	Gulo mekeda	205.6	3	Gulomekeda	205.6
4	Ahferom	217.5	4	Mereb Leke	298.2	4	Saesie Tsaeda Emba	176.9
5	Saesie Tsaeda emba	153.3	5	Saesie Tsaeda emba	176.9	5	Ganta Afeshum	233.1
6	Mereb Leke	298.9	6	Ganta Afeshum	233.1	6	T/Maichewo	208.7
7	Kafta Humera	347.6	7	T/Maichewo	208.7	7	Adwa	313.5
8	Gulomekeda	206.7	8	Medebay Zana	219.1	8	Laelay Maychew	330.6
9	Ganta Afeshum	230.4	9	Adwa	313.5	9	Tahtay Koraro	292.7
10	Tahtay Maychew	195.9	10	Laelay Maychew	330.6	10	Asgede Tsimbla	347.6
11	Medebay Zana	189.4	11	Tahtay Koraro	292.7	11	Werei Leke	322.6
12	Adwa	302.2	12	Werei Leke	322.6	12	Hawzen	183.2
13	Laelay Maychew	320.1	13	Hawzen	183.2	13	Welkait	326
14	Tahtay Koraro	281.7	14	Welkait	326	14	Atsbi Wenberta	317.9
15	Asgede Tsimbla	337.9	15	Atsbi Wenberta	317.9	15	Wukro	318.6
16	Werei Leke	307.5	16	Naeder Adet	297.6	16	Kola Temben	349.4
17	Hawzen	149.9	17	Wukro	318.6	17	Tselemti	327.2
18	Welkait	327	18	Kola Temben	349.4	18	Degua Temben	297.4
19	Atsbi Wenberta	300.1	19	Tselemti	327.2	19	Tsegede	350.6
20	Naeder Adet	276.4	20	Degua Temben	297.4	20	Enderta	343.6
21	Wukro	298.5	21	Tsegede	350.6	21	Saharti Samre	317
22	Kola Temben	334.9	22	Enderta	343.6	22	Hintalo Wejirat	340.3
23	Tselemti	316.6	23	Tanqua Abergele	308.5	23	Alaje	306.7
24	Degua Temben	284.8	24	Saharti Samre	317	24	Raya Azebo	284.6
25	Tsegede	359.6	25	Hintalo Wejirat	340.3	25	Endamehoni	281.8
26	Enderta	335.4	26	Alaje	306.7	26	Ofla	307.4
27	Tanqua Abergele	269.8	27	Raya Azebo	284.6	27	Alamata	275.8
28	Saharti Samre	294.6	28	Endamehoni	281.8		Average	288.5
29	Hintalo Wejirat	331.1	29	Ofla	307.4			
30	Alaje	305.2	30	Alamata	275.8			
31	Raya Azebo	265.3		Average	285.5			
32	Endamehoni	270						
33	Ofla	290.4						
34	Alamata	254.4						
	Average	278						

Appendix C-1:Tigray crop production statistical yield data Barley 2010 from BoARD

		Barley			
		Planted	Yield in Tone		
Number	Wereda	Hectar	Normal	Actual	YR (%)
1	Erob	387	763	351	54
2	Ahferom	2156	7481	5252	30
3	Gulomekeda	3300	10395	6204	40
4	Mereb Leke	280	826	649	21
5	Saesie Tsaeda Emba	6261	19721	10659	46
6	Ganta Afeshum	4678	15905	12176	23
7	Tahtay Maychew	866	3161	1661	32
8	Medebay Zana	68	233	130	44
9	Adwa	2189	7946	5181	35
10	Laelay Maychew	1052	3682	2453	27
11	Tahtay Koraro	8	24	11	53
12	Werei Leke	3218	9332	7846	16
13	Hawzen	5940	19008	11766	38
14	Welkait	34	116	89	23
15	Atsbi Wenberta	2618	8379	5068	40
16	Naeder Adet	432	1987	1150	43
17	Wukro	2529	8093	4288	47
18	Kola Temben	276	1003	593	41
19	Tselemti	96	307	187	39
20	Degua Temben	4478	14330	9924	31
21	Tsegede	516	1471	1187	19
22	Enderta	12005	38415	28487	26
23	Tanqua Abergele	480	864	465	46
24	Saharti Samre	3902	12487	8627	31
25	Hintalo Wejirat	9355	29935	21912	27
26	Alaje	1494	4780	3564	25
27	Raya Azebo	2425	7760	6790	13
28	Endamehoni	4658	16536	16517	30
29	Ofla	4292	15666	15022	14
30	Alamata	2352	7526	4845	36

The negative value in this table indicates that the yield of the wereda which was more than 100% during 2010.

Appendix C 2: Tigray crop production statistical yield data Wheat 2010 from BoARD

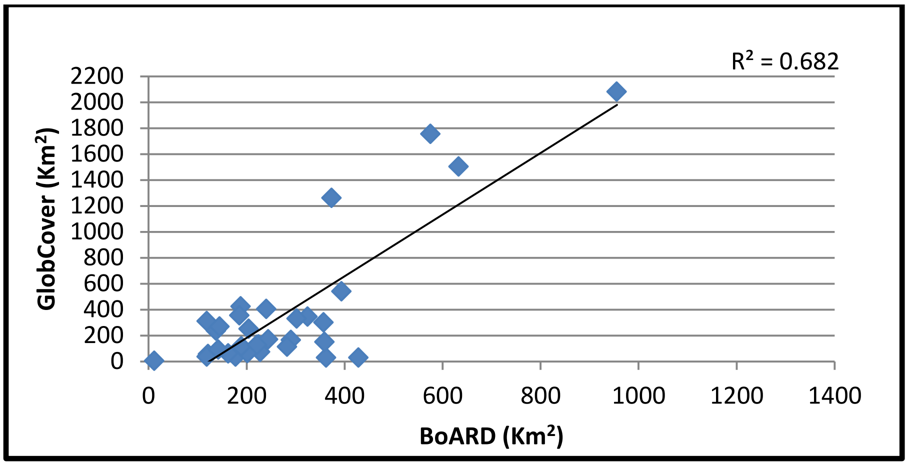
		Wheat			
		Planted	Yield in Tone		
No	Wereda	Hectare	Normal	Actual	YR (%)
1	Erob	398	836	672	20
2	Ahferom	5456	16368	16367	0
3	Gulomekeda	3587	12339	10367	16
4	Saesie Tsaeda Emba	5460	17800	11718	34
5	Ganta Afeshum	3187	12525	11141	11
6	Tahtay Maychew	2141	10555	7499	29
7	Adwa	2287	9422	9648	-2
8	Laelay Maychew	2003	8839	7537	15
9	Tahtay Koraro	60	301	180	40
10	Asgede Tsimbla	48	166	86	49
11	Werei Leke	3565	13297	12899	3
12	Hawzen	2925	11495	11757	-2
13	Welkait	357	1689	1805	-7
14	Atsbi Wenberta	5356	24102	17757	26
15	Wukro	6158	25371	17998	29
16	Kola Temben	538	1921	442	77
17	Tselemti	79	221	266	-20
18	Degua Temben	5360	22566	17709	22
19	Tsegede	3435	12366	16459	-33
20	Enderta	10780	45276	40461	11
21	Saharti Samre	3936	14170	12125	14
22	Hintalo Wejirat	11272	40241	34223	15
23	Alaje	13082	48142	45788	5
24	Raya Azebo	812	2956	2242	24
25	Endamehoni	7312	43872	31204	29
26	Ofla	7287	30314	33253	-10
27	Alamata	2369	8161	7925	3

Appendix C-3: Tigray crop production statistical yield data Teff 2010 from BoARD

No	Wereda	Teff			
		Planted	Yield in Tone		
		Hectare	Normal	Actual	YR (%)
1	Tahtay Adiyabo	407	488	558	-14
2	Laelay Adiyabo	5800	9512	9876	-4
3	Erob	7	11	8	25
4	Ahferom	5987	11974	9801	18
5	Gulomekeda	787	1259	878	30
6	Mereb Leke	2438	1950	1620	17
7	Kafta Humera	1700	3400	2575	24
8	Saesie Tsaeda Emba	30	27	25	10
9	Ganta Afeshum	174	249	224	10
10	Tahtay Maychew	4306	6158	8168	-33
11	Medebay Zana	7977	15954	14727	8
12	Adwa	3692	6719	6746	0
13	Laelay Maychew	5681	14203	10877	23
14	Tahtay Koraro	6978	14654	12560	14
15	Asgede Tsimbla	6950	13900	11254	19
16	Werei Leke	5333	10666	9866	8
17	Hawzen	1647	2767	2472	11
18	Welkait	6793	10461	13405	-28
19	Atsbi Wenberta	197	401	277	31
20	Naeder Adet	2623	5430	4377	19
21	Wukro	3599	5291	5121	3
22	Kola Temben	1710	2822	2442	13
23	Tselemti	3985	5181	6185	-19
24	Degua Temben	1702	3234	2594	20
25	Tsegede	1552	2545	2560	0
26	Enderta	4129	7680	6606	14
27	Tanqua Abergele	484	774	387	50
28	Saharti Samre	5011	7767	7443	4
29	Hintalo Wejirat	5080	9144	8043	12
30	Alaje	1528	3094	1986	36
31	Raya Azebo	14068	29543	20626	30
32	Endamehoni	622	1244	995	20
33	Ofla	936	1816	1541	15
34	Alamata	10348	21369	20732	3

Appendix D-1:Tigray Rain-fed land cover area from satellite (Globe cover) and from BoARD

No	wereda	Number of pixel from Globe			Total area in Km^2	
		Rain-fed	Mosaic	sum	Globe Rain-fed and mosaic	BoARD
1	Adwa	1030	1599	2629	236.6	137.6
2	Ahferom	194	1235	1429	128.6	225.0
3	Alaje	696	1194	1890	170.1	244.6
4	Alamata	51	268	319	28.7	362.3
5	Asgede Tsimbla	8867	10614	19481	1,753.3	575.5
6	Atsbi Wenberta	1454	1998	3452	310.7	118.8
7	Degua Temben	2323	2368	4691	422.2	187.9
8	Endamehoni	18	368	386	34.7	178.0
9	Enderta	1541	2289	3830	344.7	324.9
10	Erob	6	42	48	4.3	12.0
11	Ganta Afeshum	203	417	620	55.8	121.6
12	Gulo mekeda	39	365	404	36.4	118.9
13	Hawzen	186	483	669	60.2	162.9
14	Hintalo Wejirat	462	1196	1658	149.2	359.5
15	Kafta Humera	1432	11941	13373	1,203.6	3,968.5
16	Kola Temben	1420	2234	3654	328.9	302.4
17	Laelay Adiyabo	2845	3139	5984	538.6	394.0
18	Laelay Maychew	224	789	1013	91.2	142.7
19	Medebay Zana	1391	3105	4496	404.6	240.1
20	Mereb Leke	431	1393	1824	164.2	291.0
21	Naeder Adet	1189	1795	2984	268.6	145.2
22	Ofla	77	726	803	72.3	227.7
23	Raya Azebo	32	274	306	27.5	428.6
24	Saesie Tsaeda Emba	220	468	688	61.9	201.8
25	Saharti Samre	1068	2266	3334	300.1	357.6
26	Tahtay Adiabo	7037	9651	16688	1,501.9	633.0
27	Tahtay Koraro	1848	2091	3939	354.5	185.8
28	Tahtay Maychew	350	914	1264	113.8	189.5
29	Tanqua Abergele	383	856	1239	111.5	282.7
30	Tsegede	1321	21786	23107	2,079.6	955.8
31	Tselemti	1484	12530	14014	1,261.3	373.7
32	Welkait	4304	27593	31897	2,870.7	810.0
33	Werei Leke	366	1057	1423	128.1	221.5
34	Wukro	1215	1569	2784	250.6	204.2
	Grand Total	45707	130613	176320	15,868.8	13,549.1



Appendix D-2: Comparison GLOBCover 2009 rain-fed agriculture land cover classification and BoARD district-level cropland area data (Tigray region).

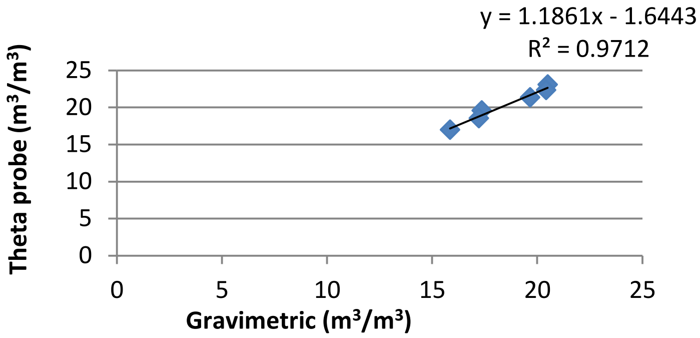
There two wereda such as Kafta Humera and Welkait are out layers and exclude from the analysis (Table Appendix 6-7).

Appendix E-1: Soil moisture content measurement using gravimetric and theta probe methods September 14/2011 to 16/2011 Adi-gudom, Tigray, Ethiopia

14/09/ 2011	sam ple	Location of sample point			weight gram			SMC m3/m3	
		N	E	Elevation	Fresh	core	Dry	Gravimetric	Theta probe
Plot 1.1	1	13.28752	39.51127	2156	219.21	103.93	202.41	17.06	22.29
	2	13.28817	39.51152	2157	243.05	102.93	224.01	15.73	14.92
	3	13.28678	39.50238	2143	214.69	101.72	199.96	14.99	16.38
	4	13.28588	39.50108	2132	276.5	103.9	245.78	21.65	24.63
plot 1.2	5	13.30435	39.49473	2144	262.34	102.45	238.52	17.51	22.09
	6	13.3075	39.49465	2152	240.08	101.44	224.02	13.10	14.27
	7	13.30963	39.49315	2158	282.57	102.31	246.26	25.22	25.34
	8	13.30882	39.49325	2154	235.3	105.93	220.38	13.04	12.44
plot 1.3	9	13.31183	39.47603	2153	222.53	102.19	208.52	13.18	13.75
	10	13.3123	39.5096	2146	240.52	102.98	218.12	19.45	22.06
	11	13.31292	39.47112	2150	234.19	102.93	216.03	16.06	19.09
	12	13.31252	39.47108	2153	266.66	104.23	245.84	14.70	13.02
Plot 2.1	1	13.2528	39.51437	2109	249.16	103.07	230.06	15.04	16.47
16/09/ 2011	2	13.27788	39.51473	2131	269.41	100.93	233.4	27.18	30.06
	3	13.27792	39.51687	2135	238.07	101.85	222.25	13.14	16.15
	4	13.27785	39.51625	2134	256.41	104.08	224.36	26.65	29.54
plot 2.2	5	13.27237	39.51652	2127	221.31	103.4	207.41	13.36	14.60
	6	13.2722	39.51562	2126	259.89	103.08	228	25.53	29.39
	7	13.26192	39.5182	2108	223.37	103.46	206.84	15.99	16.19
	8	13.26307	39.51757	2109	245.9	104.15	215.93	26.81	29.22
plot 2.3	9	13.26628	39.51498	2113	220.08	102.45	205.97	13.63	14.52
	10	13.26902	39.51498	2116	240.65	102.84	214.14	23.82	29.06
	11	13.26542	39.51288	2113	247.34	105.61	229.51	14.39	14.00
	12	13.26772	39.51268	2122	242.78	102.81	213.16	26.84	27.74

Appendix E-2:Soil moisture content result from gravimetric method and theta probe

plot number	Gravimetric(m^3/m^3)	Theta probe(m^3/m^3)
1	17.36	19.56
2	17.22	18.54
3	15.85	16.98
4	20.50	23.06
5	20.42	22.35
6	19.67	21.33
Average	18.50	20.30



Appendix E-3: Soil moisture content September 14 and 16/2010.

The soil moisture content of the study area during the data collection was indicated in Table 6-8 and there is a high correlation between gravimetric and theta probe methods.